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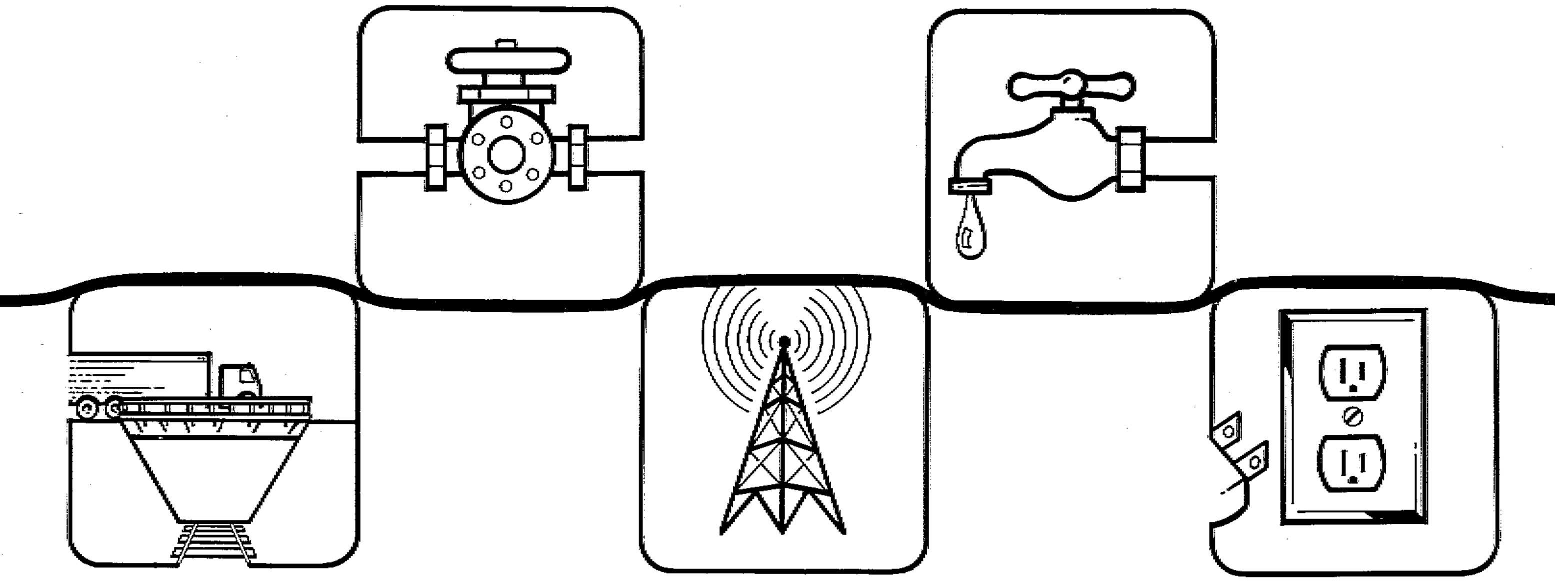
Collocation Impacts on the Vulnerability of Lifelines During Earthquakes with Applictions to the Cajon Pass, California



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Collocation Impacts on the Vulnerability of Lifelines During Earthquakes with Applications to the Cajon Pass, California

Submitted to the Federal Emergency Management Agency
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Submitted by:

INTECH Inc.
11316 Rouen Dr.
Potomac, MD 20854-3126

Co-Principal Investigators:
Dr. Phillip A. Lowe, INTEC, Inc.
Dr. Charles F. Scheffey, INTEC, Inc.
Mr. Po Lam, Earth Mechanics, Inc.

COLLOCATION IMPACTS ON THE VULNERABILITY OF LIFELINES DURING EARTHQUAKES WITH APPLICATION TO THE CAJON PASS, CALIFORNIA

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1.0 CONCLUSIONS

The purpose of this study was to:

develop a management screening tool that can be used by lifeline owners, designers and providers, operators, users, and regulators to sort through numerous collocation conditions to identify the critical locations and to provide an estimate of the increased risk that results when such collocated facilities are subjected to an earthquake event; and to

analyze the Cajon Pass, California, situation to demonstrate how the screening tool can be used and to examine specific conditions at the Pass.

The resulting screening tool is an important development for several reasons:

1) it is the first documented method for examining multiple collocation conditions and it is applicable to all lifeline facilities. As improvements are made in the fundamental analysis methods for individual lifelines or earthquake conditions, they readily can be introduced into the screening tool to improve its predictive ability;

2) its use can identify the most critical collocation conditions at a specific study area, thereby allowing limited resources to be focused on the most important conditions for improving the overall ability of the lifelines to survive an earthquake event;

3) its use can identify technical areas of uncertainty and/or poor siting practices. This can identify the need for and lead to further research and studies to reduce the identified technical uncertainty or it can identify ways to mitigate siting practices that are more vulnerable to inducing collocation failure conditions; and

4) by being documented and made widely available by the Federal Emergency Management Agency, it is anticipated that it will stimulate the earthquake and lifeline communities to developed improvements in the analysis method or even to develop new, improved screening methods.

The development of the analysis methodology as well as its test application to the Cajon Pass has highlighted several important conclusions.

- Lifeline collocation can produce both benefits and increased risk of failure during earthquake events. A benefit of closely located transportation lifelines is that the second lifeline can provide the detour or access route to the damaged sections of the first lifeline. However, intersecting lifelines generally result in the failure of one lifeline increasing the risk of failure of the lifeline(s) it crosses.

- It is understandable that topographic conditions have led to the routing of lifeline systems in corridors. However, manmade considerations that force the lifeline owners to use the same rights-of-way for widely different lifelines (for example, locating petroleum fuel pipeline and communication conduits next to each other, routing natural gas pipelines back and forth under a railroad bed, and having a mix of lifelines cross the earthquake fault zone at the same location) greatly increase the risk of failure for the individual lifelines and the complications that will be encountered during site restoration after an earthquake.

- As compared to buildings, ground movement is more important that ground shaking for lifeline components, especially buried lifelines and electrical transmission towers. This means that much of the technical data base on earthquake shaking intensity is not critical for lifeline analysis, whereas important ground movement data and analyses are not as well developed as the shaking intensity data. This suggests that future studies need to emphasize obtaining ground movement information.

- A very useful screening tool has been developed during this study. The tool can be used to identify the critical lifeline collocation locations and the conditions that make them critical. It can identify areas of technical uncertainty and poor siting practices, and its use can identify important research and development activities that can lead to lowered risk of collocation-induced lifeline failures. It will be of value to lifeline owners, designers and providers, operators, users, and regulators.

- The analysis tool has been successfully applied to the Cajon Pass, California. It has identified that for this semi-desert region that:

    The Cajon Junction, Lone Pine Canyon (which contains the San Andreas fault zone), Blue Cut, and the area just south of the interchange between I-15 and I-215 are the critical locations in terms of collocation impacts at the Cajon Pass.

    Fuel pipeline failures have the greatest impact on the other lifelines during the immediate recovery period after an earthquake.

Current siting practices for fiber optic cables indicates that more severe telephone communication failures than have been experienced in past earthquakes can be anticipated in future earthquakes when fiber optic systems have become more dominant in providing the basic telephone service.

Lifeline siting practices have not fully considered the impacts that a new lifeline will have on existing lifelines and, conversely, the impacts that the existing lifelines will have on the new lifeline.

Transportation lifeline restoration of service is highly dependent on sequentially repairing the lifeline damage as the lifeline itself is needed to provide access to the next damage location. Parallel repair operations are more probable for the other lifeline systems.

Communication, electric power, and fuel pipeline lifelines can generally be analyzed as a set of discrete collocation points. The restoration of service at any one point is not a strong function of the restoration work that is needed at other collocation points. Thus, if there is a restoration problem that will take a long time compared to the other locations, it becomes the "critical path" that sets the time period for the restoration of the entire lifeline system.

When multiple lifelines of the same class are collocated (such as installing all fiber optic cables or all fuel pipelines in the same or parallel trenches) or when multiple different lifelines intersect at a common point, the reliability of each individual lifeline decreases to the value of the "weakest link" of the combined lifeline systems. In addition, repair times increase because of local congestion and the concern that work on one lifeline component could lead to damage of the other different lifeline components.

- There is a need for further collocation lifeline studies: to apply the newly developed screening tool to other locations to assure that the methods can be transferred to other U.S. locations and to analyze different lifelines, geographic, and earthquake conditions; and to develop data and approaches that can be used to further improve the predictive capabilities of the screening tool.

2.0 INTRODUCTION

2.1 Background

Lifelines (e.g., systems and facilities that deliver energy and fuel and systems and facilities that provide key services such as water and sewage, transportation, and communications are defined as lifelines) are presently being sited in "utility or transportation corridors" to reduce their right-of-way environmental, aesthetic, and cost impacts on the communities that rely upon them. The individual lifelines are usually designed, constructed, and modified throughout their service life. This results in different standards and siting criteria being applied to segments of the same lifeline, and also to different standards or siting criteria being applied to the separate lifelines systems within a single corridor. Presently, the siting review usually does not consider the impact of proximity or collocation of the lifelines on their individual risk or vulnerability to natural or manmade hazards or disasters. This is either because the other lifelines have not yet been installed or because such a consideration has not been identified as being an important factor for such an evaluation.

There have been cases when some lifeline collocations have increased the levels of damage experienced during an accident or an earthquake. For example, water line ruptures during earthquakes have led to washouts which have caused foundation damage to nearby facilities. In southern California a railroad accident (transportation lifeline) led to the subsequent failure of a collocated fuel pipeline, and the resulting fire caused considerable property damage and loss of life. Loss of electric power has restricted, and sometimes failed, the ability to provide water and sewer services or emergency fire fighting capabilities.

In response to these types of situations, the Federal Emergency Management Agency (FEMA) is examining the use of such corridors, and FEMA initiated this study to examine the impact of siting multiple lifeline systems in confined and at-risk areas.

The overall FEMA project goals are to develop managerial tools that can be used to increase the understanding of the lifeline systems' vulnerabilities and to help identify potential mitigation approaches that could be used to reduce those vulnerabilities. Another program goal is to identify methods to enhance the transfer of the resulting information to lifeline system providers, designers, builders, managers, operators, users, and regulators.

This report is the second of a series of three reports. The first report[(1)*] presented an inventory of the major lifeline systems located at Cajon Pass, California, and it summarized the earthquake and geologic analysis tools available to identify and define the

* The numbers in superscript are references found at the end of each chapter.

level of seismic risk to those lifelines. This report presents the analytic methods developed to define the collocation impacts and the resulting analyses of the seismic and geologic environmental loads on the collocated lifelines in the Cajon Pass. The assumed earthquake event is similar to the 8.3 magnitude, San Andreas fault, Ft. Tejon earthquake of 1857. In this report a new analysis method is developed and applied to identify the increase in the vulnerability of the individual lifeline systems due to their proximity to other lifelines in the Cajon Pass. A third report[2] presents an executive summary of the study. The Cajon Pass Lifeline Inventory report and this present report taken together provide a specific example of how the new analysis method can be applied to a real lifeline corridor situation.

2.2 Study Approach

The approach used to develop the information for this report was as follows. The Cajon Lifeline Inventory report[1], additional information provided during direct meetings with the lifeline owners, site reconnaissance surveys to validate the information and to examine specific site conditions of interest to the study, and existing literature that describes lessons learned from actual earthquake events were compiled and thoroughly studied. The principal investigators then hypothesized an analysis method that could be applied to the Cajon Pass lifelines to estimate the impacts of proximity on their earthquake-induced performance and repairs.

This analysis method emphasizes building upon existing data bases and analytic methods. In applications, it is recommended that the analyses, studies, and information available from the lifeline owners be used whenever possible. In the event that sufficient data on the lifeline response to earthquakes and the expected time to restore the lifeline back to its required service level are not available from the lifeline owners, the analytic methods, with some important modifications, of "Earthquake Damage Evaluation Data for California", ATC-13[3] are recommended as an appropriate alternative analysis method. In this project the "most probable restoration time" was defined as the analysis parameter that best could be used to define the impact of lifeline proximity on the individual lifeline's earthquake vulnerability.

The resulting method was then applied to the Cajon Pass lifelines. The U.S. Geologic Survey's digitized topographic map of the Cajon Pass and the contiguous quadrangles were utilized. The commercial, computer aided, design program AutoCAD was used as it is readily available to the public, thus the methodology is not limited to being dependent upon a specialized or proprietary computer program. With this tool, overlays of the lifeline routes with seismic and geologic information presented in the inventory report[1] were used to identify the conditions and locations where the individual lifelines were most vulnerable to the hypothesized earthquake. The analysis methods described in Section 4.0 of this report were then applied to the lifelines and the results are presented in Section 5.0. Section 6.0 identifies future studies that could be undertaken to further qualify the analysis methods and to improve the details of the specific analysis activities. Section 3.0 provides a summary of the study.

As part of the study validation process, the draft results of the study were submitted to the project advisors, see Table 1, for their independent professional evaluation and to the lifeline owners and regulators who provided information for the preparation of the report or the Cajon Pass Inventory report. FEMA also sent draft report copies to a select list of independent reviewers. Each comment received was addressed, and this final report then was prepared and submitted to FEMA.

Table 1
CAJON PASS IMPACTS OF LIFELINE PROXIMITY:
EXPERT TECHNICAL ADVISORY GROUP

William S. Bivins	T.D. O'Rourke
James H. Gates	Dennis K. Ostrom
Le Val Lund	Kenneth F. Sullivan
John D. (Jack) McNorgan	

2.3 Chapter 2.0 Bibliography

1. P. Lowe, C. Scheffey, and P. Lam, "Inventory of Lifelines in the Cajon Pass, California", ITI FEMA CP 120190, August 1991.

2. P. Lowe, C. Scheffey, and P. Lam, "Collocation Impacts on Lifeline Earthquake Vulnerability at the Cajon Pass, California, Executive Summary", ITI FEMA CP 050191-ES, August 1991.

3. C. Rojahn and R. Sharpe, "Earthquake Damage Evaluation Data for California", ATC-13, 1985.

3.0 SUMMARY

This report presents a systematic approach to calculate the impacts due to the collocation or close proximity of one lifeline to another during earthquake conditions. Specifically, the collocation vulnerability impact is defined as the increase in the most probable time to restore the lifeline to its intended level of service. The analysis methods proposed are intended to be used in screening analyses that determine which lifelines or lifeline segments are most impacted by the collocation or close proximity of other lifelines. Once the critical locations or conditions are known, it may be equally important to reanalyze them using more detailed analyses to further define the collocation impacts.

The methods proposed are to use the best available information to determine the lifeline damage state, the probability that the damage state or greater will occur, and the time to restore the lifeline to its intended service. Normally, such information is obtained from the lifeline owner/operator. However, a alternative method is proposed when such information is not available from that source.

The alternative method is based on building upon existing earthquake damage information and analysis methods which have been compiled by the Applied Technology Council (ATC). In that manner, the analysis results can be compared with earlier or future studies that use the data base without the need to compare or justify the data base. However, important improvements to the existing ATC data base also are presented.

Collocation impacts can be described in one of two broad terms: 1) the resource impacts (i.e., the increase in personnel, equipment, and material resources) that are required to return the total lifeline system to its needed operating capacity. This is performed in the present method by summing the impacts at each component along the entire lifeline route. 2) the resource impacts at a specific location where multiple lifeline components are located. In both cases, the present method uses the most probable time to restore the lifeline component or system to its needed operating capacity as the appropriate measure of the resource impacts.

The analysis method has been applied to the lifeline systems in the Cajon Pass, California, as a test case. It is clear that the communication, electric power, and fuel transmissions lifeline systems that have the potential for collocation impacts are, in general, not very sensitive to earthquake ground shaking for shaking intensities represented by Modified Mercalli Intensity indices of VIII or less (these are the values found at Cajon Pass for the assumed earthquake event). They are, however, very sensitive to ground movement expressed as fault displacement, landslides, or lateral spreads. Bridges are sensitive to both ground shaking and ground conditions (displacement, landslide, lateral spread, and local liquefactions at their foundation locations).

It is understandable that topographic conditions have led to the routing of lifeline systems into corridors. However, manmade considerations that force the lifeline owners to use the exact same rights-of-way for widely different needs (for example, locating petroleum fuel pipeline and communication conduits next to each other, routing natural gas pipelines back and forth under a railroad bed, and having a mix of lifelines cross the earthquake fault zone at the same location) greatly increases the individual lifeline risks and the complications that will be encountered during site restoration after an earthquake.

The Cajon Pass example has identified that the communication, electric power transmission, and fuel pipeline lifelines generally can be analyzed as a set of discrete collocation points. The restoration of service at any one point is not a strong function of the restoration work that is needed at other collocation points. Thus, if there is a restoration problem that will take a long time compared to the other locations, it becomes the "critical path" that sets the time period for the restoration of the entire lifeline system. Transportation lifeline collocation points, however, are sensitive to the damage that has occurred along the route of the transportation system. That is, often it is necessary for the heavy equipment and material needed to have access to the damage location by traveling along the highway or railroad itself. Thus, before access to a particular bridge can be made, it may be necessary to first repair all the damage sites on the route prior to that location.

4.0 ANALYSIS METHOD

In performing an analysis of the impacts of collocation or close proximity on lifeline systems and components for earthquake or other at-risk conditions, it is important that the most accurate data and analyses be used to characterize the response of the individual lifelines to the loads applied. Whatever method is applied must be applicable to all the components within the lifeline system, because the evaluation of the collocation impacts requires comparing the calculated time to restore the lifeline to its intended service for both the collocation and an assumed non-collocation condition. The general methods for performing such an analysis are shown in the flow chart of Figure 1. If owner-supplied or site specific analysis methods are not available for use in the detailed calculations, the following material (Sections 4.1, 4.2, 4.3, and 4.4) can be used as the alternative analysis method. This is discussed more fully in the following material.

Figure 1 shows a four step approach that can be used to analyze any lifeline under at-risk conditions (e.g., an natural or manmade disaster condition). However, the present study only develops the detailed information needed to analyze earthquake conditions. The steps are:

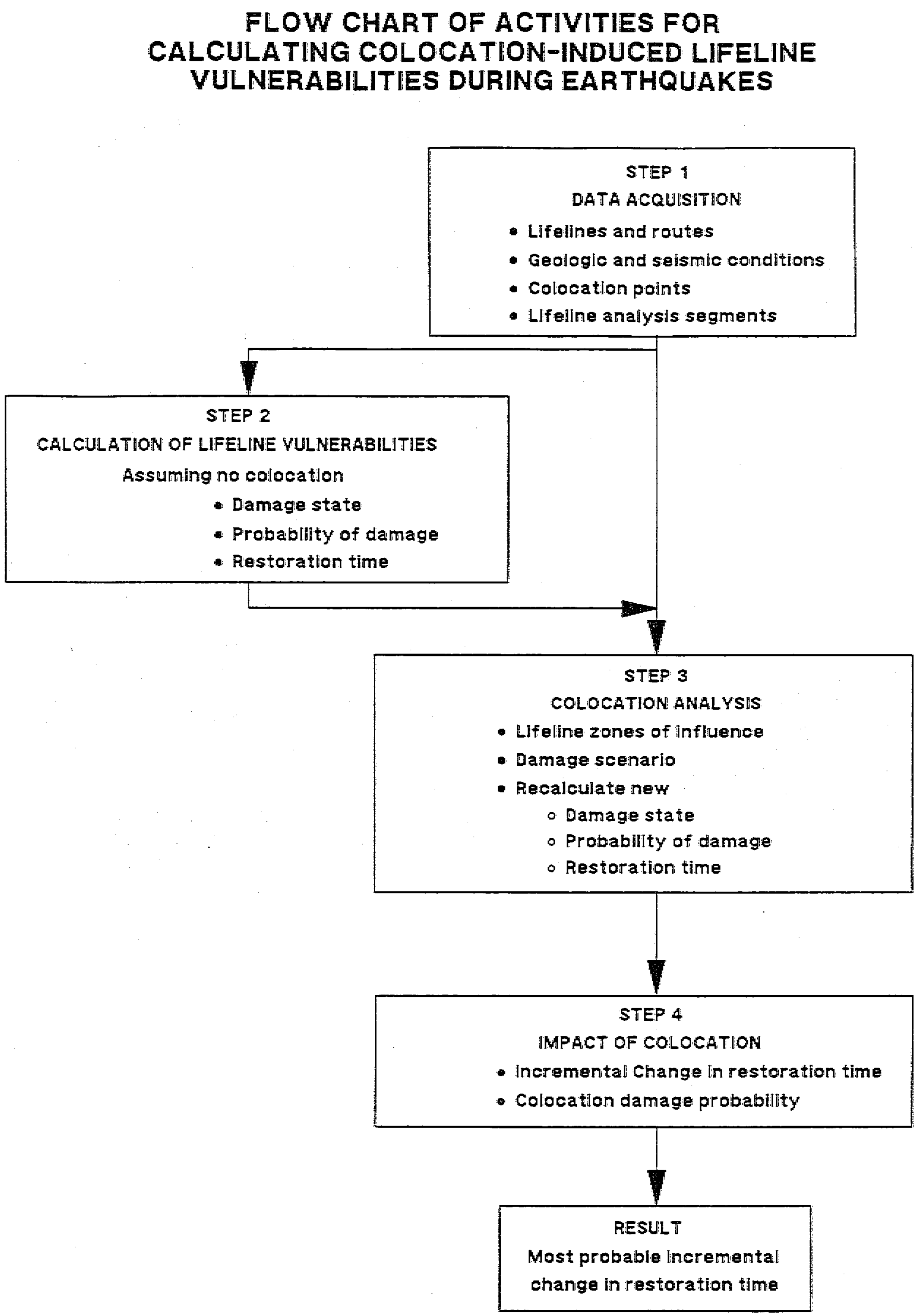
1) Data Acquisition;
2) Calculation of Lifeline Vulnerability;
3) Collocation Analysis; and
4) Interpretation of the Collocation Impacts.

Briefly, these activities include:

<u>Data Acquisition</u>

This task is to assemble all of the information that defines the lifelines and their routes as well as the geologic and seismic

Figure 1, FLOW CHART OF THE ANALYSIS METHOD



conditions that will place loads on the lifelines. Some analysis and organization of the resulting information is included in this step to facilitate the application of the analysis method to the specific conditions of interest. Such analyses include identifying the collocation sites as well as dividing the lifelines into consistent sections for subsequent analysis.

Calculation of Lifeline Vulnerability

The geologic conditions identified during the data acquisition are used as input to a seismic analysis. Such data include the topology of the area being studied, a description of the sediment and rock structures, locations of water, and identification of surface ground slopes. Seismic conditions include identifying the location and type of the anticipated earthquake. These are used to estimate the earthquake shaking intensities (it is recommended that Modified Mercalli Intensity (MMI) indices be used to characterize the shaking intensity) and earthquake-induced landslides and soil liquefaction locations.

During this analysis step, the earthquake intensities and ground movements are use to determine the vulnerability of each lifeline at each collocation site as if it were the only lifeline at that site (e.g., as if there were no collocation there). Based on the design and placement of the lifeline component or segment and the seismic loads placed on it, the resulting damage state, probability that the damage state will occur, and the time required to restore the lifeline to its intended service can be calculated. The restoration time is the sum of the time to repair the lifeline assuming all the equipment, material, and repair personnel are available at the damage location, plus the access time required to transport them to the damage location, plus the time required to have them available to transport to the site.

If owner-supplied damage information is not available, it is recommended that the analysis methods, as modified in this report, of "Earthquake Damage Evaluation Data for California", ATC-13, 1985, (prepared by the Applied Technology Council of Redwood City, California) be used. When a study is to be performed for locations outside of California, professional judgement must be applied to determine how to adjust, if at all, the data base of ATC-13. The methods of "Seismic Vulnerability of Lifelines in the Conterminous United State, ATC-25, (presently in print at the Applied Technology Council, and identified as reference 20 in this report section) can be considered for use. However, it is noted that the consistency and validity of the ATC-25 approach has not been examined during the present study, and thus the methods of that study can not be recommended by the Principal Investigators of the present study. It is identified here for information only.

Collocation Analysis

This analysis step builds upon the results obtained from the previous two analysis steps. Based on the actual anticipated damage states for each lifeline at the collocation site as determined in the previous analysis step, a collocation interaction scenario is postulated. The scenario can change either the damage state, the probability that the damage will occur, the restoration time (typically only the access time would be changed and the repair time then would be a new calculation), or any combination of those items. After the individual items are specified, the remaining items (i.e., the non specified damage state, probability, or repair time) are determined using the calculation method applied in the previous analysis step.

Interpretation of the Collocation Impact

This analysis step uses the calculated information of the two previous steps to characterize the impact of lifeline collocation. The most realistic measure of the impact is the "most probable incremental change in the restoration of service time". This is defined as the product of the probability of collocation damage occurring times the incremental increase in restoration of service time (the incremental change in the time to restore service is the restoration time for collocation minus the restoration time with no collocation considered).

Additional details on the recommended analysis approach are provided in Sections 4.1, 4.2, 4.3, and 4.4 below.

4.1 Data Acquisition

Lifeline and Geologic Information

Data acquisition is the first step of any lifeline vulnerability analysis. Information is needed to define the lifelines and their routes as well as to define the geologic and seismic conditions that apply to the lifelines of interest.

Information on the lifelines can be obtained from a number of sources. It is recommended that a site reconnaissance visit be conducted first to help the researchers understand the physical conditions and to preliminarily define the lifelines of interest. In addition, maps from the U.S. Geologic Survey (such as topographic maps published at the quadrangle scale of 1:24,000), state departments of natural resources or mines and geology, the U.S. Forest Service, and highway maps are excellent sources of data. They often indicate lifeline components and routes as well as identify geographic features. The U.S. and state geologic surveys (or departments of mines and geologies, etc.) will also have maps and studies that characterize the earthquake faults, ground units (e.g., the types of sediments and rock formations in the areas of interest), landslide locations, water table data, etc.. State offices of emergency response (such as offices of emergency preparedness or seismic safety offices), fire marshal offices, state public utility commissions, water boards and commissions, and the general professional literature on earthquakes are other important sources of information on lifelines and the potential geologic/seismic conditions of interest.

The single most important source for lifeline information is the owner/operators. They will each have detailed route maps and details on their design, construction, and installation. However, as built drawings and construction information are frequently different than the "design" information. Thus, it is important to discuss the information received with the suppliers, and to validate the understanding received with data from other sources and site reconnaissance visits.

Once the applicable lifeline data has been assembled, the lifeline collocation or close proximity locations in the study region should be identified and given a reference number. Also, each lifeline should be divided into convenient segments that are reasonably uniform in their characteristics. These activities are done to aid in the subsequent analysis steps. The application of the analysis algorithms (to be described below) can be separately applied to each lifeline collocation location, using the list of collocation location points as a check that all the needed locations were considered, and using the lifeline segments to identify the physical conditions at the collocation point being analyzed.

The lifeline segments or divisions selected for analysis should be reasonably "uniform" in that the lifeline components should be similar within the segment, the shaking intensity (as measured by the Modified Mercalli Intensity (MMI)) index should be similar, the ground conditions should be similar (that is, areas of ground movement should be analyzed separately from areas of stable ground), and access for repair crews, equipment, and material to the lifeline proximity points along the segment should be reasonably the same. With this approach, lifelines, such as buried pipelines or electrical transmission lines, can be divided into long segments. Their division is primarily set by the ground conditions and the MMI values. Other lifeline systems that have frequent component changes in them, such as transportation systems that include bridges separated by roadbeds, need to be separated by component and access route, and sometimes the roadbed must be further divided to account for ground condition or MMI changes.

Whenever possible, standard measures of earthquake events should be used to characterize the seismic conditions in the study area. In this way the results of the study more readily can be compared with other published data, which allows the conclusions to be validated by such other available information. Thus, earthquake magnitude or the earthquake "size" can be represented by the Richter scale.

Ground Shaking Intensity

Several methods to characterize the intensity of the shaking of an earthquake were considered. Items considered included the magnitude and extent of the shaking. Although ground acceleration, velocity, and displacement are more appropriate for evaluating specific lifeline designs, the use of intensity scales are more dominant in the literature. Rossi-Forell (RF) and Modified Mercalli Intensity (MMI) scales are commonly used as a measure of intensity. MMI is recommended for use since it is more widely used in the earthquake literature, although it is a subjective scale that is dependent on individual interpretation of its meaning. Appendix A presents the detailed definitions of MMI.

The MMI scale includes 12 categories of ground motion intensity from level I (not felt) to level XII (total damage). The use of Roman numerals was done to discourage analysts from trying to consider half scale values. This further implies that the MMI is a broad measure of the shaking intensity. The individual MMI scales are almost exclusively characterized in terms of building damage, so their usefulness for modern lifeline structures and components is somewhat restricted. ATC-13(2) provides a detailed estimate of lifeline damage probability as a function of the MMI scale. As an example of potential interpretation problems, the MMI scale IX identifies that "underground pipes are sometimes broken" while ATC-13 for MMI = IX estimates in California that pipe breaks will occur with a total probability of 91.3%. This illustrates the subjective nature of the MMI scale. Nevertheless, it is commonly used to characterize earthquake intensity, and for consistency it recommended as the proper characterization parameter for examining the collocation impacts on lifeline vulnerability to earthquakes.

Although there are two computer models(3,4,5) that calculate earthquake intensity and that are applicable to the conterminous U.S., the Evernden(3,4) model is recommended because it has been verified by comparison with historical earthquakes, it incorporates the local sediment conditions and such sediment conditions are generally available in the national U.S. Geological Survey geologic data base and in the data bases of the various state offices of mines and geology or natural resources, it is easy to use, it is readily available to researchers, lifeline owners, and to others who may need to apply the methods of this study to other regions in the U.S., and it facilitates comparisons of this research with that of others(7) who have used the Evernden Model. The Advisors to this Project were concerned that the Evernden model may not be as accurate near the earthquake fault location (it appears to underestimate the MMI values there) as it is in predicting the far field effects. Discussions with the staff of the California Division of Mines and Geology confirmed that they had similar concerns. The recommended solution is to increase the calculated MMI value by one scale level at locations near the earthquake fault zone. For most lifeline components this is expected to have a small impact, because the fault displacement effects there are expected to overshadow the shaking effects represented by the increased MMI value.

The Evernden model has been coded in a computer program, QUAK2NW3. Appropriate input data files are available with the model, and they were verified for use in the present study. They include:

(1) a fault data file that identifies the location of the geologic fault by a series of uniform point sources. They can be spaced as closely as desirable.

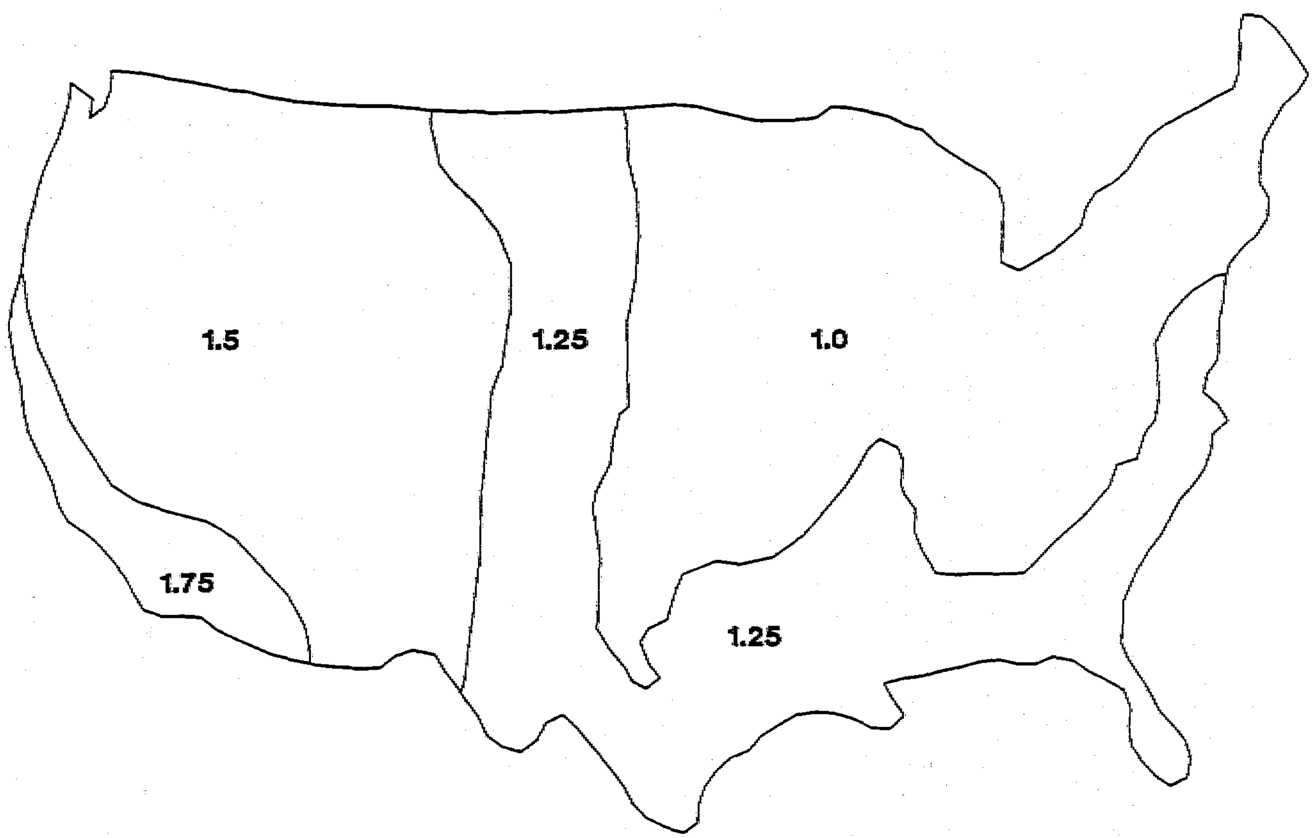
(2) a ground condition file that identifies the soil conditions (soil and ground geologic units or descriptions). The spacing of these ground units provides the calculation grid for the program. Evernden typically organizes the ground condition into 0.5 minute latitude by 0.5 minute longitude grids, and they were used for the present study.

(3) a pseudodepth term "C" which is chosen to give the proper near-field die-off of the shaking intensities. Evernden has previously analyzed earthquakes along the San Andreas fault, and his value of C (10 kilometers) was used in this study. Values for other faults can be selected with consultation with Dr. Evernden or by professional judgement.

(4) an attenuation parameter "k" which controls the rate of die-off of peak acceleration as a function of distance from the fault being analyzed. Evernden has identified a value for coastal California, eastern California and the Mountain States, the Gulf and Atlantic Coastal plains, and the rest of the eastern U.S., and these values are shown in Figure 2. The coastal California value was used in this study, $k = 1.75$.

With the above input, QUAK2NW3 computes the acceleration associated with the energy release along each position of the fault. Earthquake intensities are calculated in terms of the Rossi Forell scale, and then the MMI value is computed from a correlation that Evernden developed for that purpose. The intensity is first computed for a reference ground unit condition (e.g., saturated alluvium), and then the intensity value at each grid point is adjusted for the actual ground condition specified in the ground condition file. The output of QUAK2NW3 can be used as input into a digital plotting program, so that the regions of uniform MMI index can be automatically plotted over the routes of each lifeline system studied. In the present study the commercially available program "AutoCAD" was used, although other similar programs would be just as appropriate. An important criteria for the selection of the plotting program is that it should be able to read the

Figure 2, THE "ATTENUATION PARAMETER k" FOR USE IN CALCULATING EARTHQUAKE SHAKING INTENSITY



APPROXIMATE PATTERN OF ATTENUATION CHARACTERISTICS (k-VALUE DISTRIBUTION) THROUGHOUT THE CONTERMINOUS UNITED STATES

ditigitized files of the U.S. Geological Survey topographic maps. Those maps include the routes of many of the lifelines and the geographic elevation contours. Later when ground slopes are needed to calculate landslide and liquefaction potential, the computer program can be used to automatically perform the calculations. Thus, a single program can conveniently incorporate and graphically present all the key data: lifeline location, fault traces, MMI values, and ground slopes.

Selection of the Earthquake Event

The next step is to identify the earthquake event for the analysis. Based on the faults in or near the study region, the QUAK2NW3 program can be used to perform a sensitivity evaluation to identify the appropriate earthquake event. All that is required is to input various earthquake events (length and location of the fault movement, the ground conditions, the depth of the earthquake, and the attenuation parameter). The results of several analyses can then be compared to identify the most realistic event for the analysis. Key additional data that should be considered is the prediction of the magnitude and the probability that an earthquake will occur near or in the study region. Such predictions are available from Federal and state seismologic offices.

4.2 Calculation of Lifeline Vulnerability

Again, it is recommended that the lifeline owners/operators be consulted to determine if they already have detailed calculations on their lifeline's vulnerability to earthquake events. If so, that approach may be the most detailed available. As an alternative, the following sections identify how the ATC-13 information, with important modifications, should specifically be used if such owner/operator information is not available.

Damage Assessment

To determine the potential damage state that occurs, the impacts of shaking, fault displacement, and soil movement due to either landslide or liquefaction conditions have to be considered. The total damage state is the sum of these individual components; however, if one of these components dominates the others it can be used without adding the other damage states (this is often the actual situation). However, when that is done a similar approach must be used for both the analysis performed while assuming no collocation impacts and for the analysis performed while assuming collocation impacts. Also, adding the separate damage states may over estimate the total damage state. Knowledge of the physical situation and professional judgement must be applied to determine the realistic total damage state.

There are seven categories of damage state defined in ATC-13. They are shown in Table 2.

Table 2
ATC-13 DEFINITION OF LIFELINE DAMAGE STATE

Lifeline Damage State No. Description	For Non Pipeline Lifelines % Damage	For Pipeline Lifelines Breaks/kilometer	For Pipeline Lifelines % Damage
1 - None	0	0	0
2 - Slight	0.5	0.25	0.6
3 - Light	5	0.75	2
4 - Moderate	20	5.5	14
5 - Heavy	45	15	38
6 - Major	80	30	75
7 - Destroyed	100	40	100

In the present method, the important parameter is the identification of the Damage State Number, a number from 1 to 7. Thus, percent damage or breaks per kilometer are not the needed variable. The experts that developed ATC-13 used the following definitions for damage state: percent damage meant the estimate of the dollar value of the earthquake damage divided by the dollar cost to replace the entire lifeline. However, for pipelines they were asked to think in terms of breaks in a pipeline per kilometer of pipeline length. Within a kilometer segment, 15 breaks may actually cost the same as 40, since the expected procedure would be to simply replace the entire kilometer length rather than to make such a large number of individual repairs and still be concerned that an additional partial break was undiscovered and thus remained unrepaired. Similarly, an electrical transmission tower with 45% physical damage would probably be replaced entirely, as it would not be worth the risk to the owner to make such extensive repairs when a new tower may be less expensive to install and certainly would be more reliable in the future. Thus, when the ATC-13 definition is applied to a large number of similar lifeline components, then, on the average, the damage state may properly predict the condition of the sum of the individual repair costs divided by the total replacement costs for all the components.

However, in the present analysis method, the ATC-13 data will be applied to individual lifeline components. It is acceptable to use the data in this manner as it provides an expert knowledge base for estimating the damage state, and the final result of interest in the present analysis method is not the damage state but a time to restore lifeline service. Its use for single lifeline components would be less accurate if the desired result were the percent damage to be used to calculate a cost of repair (that is, ATC-13 is more accurate for costs averaged over a large number of cases than it would be for a single case). The proposed analysis method could, however, be improved if a new expert opinion study of the damage state and probability for that damage state for single lifeline components were to become available.

The following material indicates how the data of ATC-13 are proposed for use in evaluating the collocation impacts of lifelines during earthquake events.

Shaking Damage

The shaking impact of the earthquake event can be estimated by using Table 7.10 (pages 198-217) of ATC-13. For convenience, the more frequently needed tables for lifeline analysis are reproduced in this report as Table 3.

These tables present the collective judgement of the probability that a class of lifeline components will incur a given damage state level, as a function of the Modified Mercalli Intensity (MMI) index. They were developed by using a modified Delphi method that employed a large number of experts who provided their opinion as to what was the probability that a damage level would be experienced for a given imposed value of shaking intensity, MMI.

The trend in the probability data would normally be expected to show that, as the MMI increases, more of the lifeline components would be expected to experience higher damage states. Thus, for increasing values of MMI, the shape of the probability curve should be expected to have its peak value move towards higher damage states and the magnitude of the peak value decrease as the width of the probability curve increases. However, at MMI = XII the probability curve should again focus over the narrow band of damage states 6 and 7. The information for bridges, highways, and buried pipelines and conduits follow this pattern. It is less evident for electrical transmission towers and railroads. The methodology for calculating shaking damage collocation impacts, because it is based on the ATC-13 data, will be less accurate for electrical transmission towers and railroads, compared to buried pipeline and conduits, highways, and bridges. Still, the Principal Investigators and Advisors for this project judged that the data was adequate for the analysis purposes proposed in this report.

In Table 3 the lifeline items are: Facility Class 24-multiple single span bridges; Facility Class 25-continuous/monolithic bridges; Facility Class 31-underground pipelines; Facility Class 47-railroads; Facility Class 48-highways; Facility Class 55-electrical towers less than 100 feet high; and Facility Class 56-electrical towers more than 100 feet high.

In this report the ATC-13 shaking damage data is used in the following manner. For the lifeline component or segment being considered, the appropriate table is entered using the MMI value at the collocation being analyzed. The table is entered to identify the greatest probability value in the column under the MMI listing. In the sample below enter the table (on page 21) for MMI = VIII. Reading to the left of that maximum probability, the most probable damage state is then read from the left most column.

Table 3
SHAKING DAMAGE PROBABILITY MATRICES, ATC-13 Tables 7.10

Damage Probability Matrices Based on Expert Opinion for Earthquake Engineering Facility Classes

Damage State

Modified Mercalli Intensity

Multiple Single Span Bridges

	VI	VII	VIII	IX	X	XI	XII
1	3.0	***	***	***	***	***	***
2	97.0	12.3	***	***	***	***	***
3	***	85.7	70.9	***	***	***	***
4	***	***	29.1	71.1	***	***	***
5	***	***	***	28.9	82.4	***	***
6	***	***	***	***	16.9	100.0	***
7	***	***	***	***	***	***	100.0

Continuous/Monolithic Bridges

	VI	VII	VIII	IX	X	XI	XII
1	93.6	8.1	0.9	***	***	***	***
2	6.4	77.8	17.6	***	***	***	***
3	***	14.1	78.6	56.5	***	***	***
4	***	***	2.9	43.5	1.8	1.2	0.7
5	***	***	***	***	98.2	36.8	5.7
6	***	***	***	***	***	61.9	39.1
7	***	***	***	***	***	0.1	54.5

Underground Pipelines and Conduits

	VI	VII	VIII	IX	X	XI	XII
1	100.0	99.8	20.9	8.7	***	***	***
2	***	0.2	54.1	34.2	1.3	***	***
3	***	***	17.2	36.1	7.9	0.5	***
4	***	***	7.8	21.9	89.5	66.5	4.5
5	***	***	***	***	1.1	29.6	56.4
6	***	***	***	***	0.2	3.3	37.9
7	***	***	***	***	***	0.1	1.2

***Very small probability

Table 3 (Continued)
SHAKING DAMAGE PROBABILITY MATRICES, ATC-13 Tables 7.10

Damage State — Modified Mercalli Intensity

Railroads

Damage State	VI	VII	VIII	IX	X	XI	XII
1	94.1	9.8	0.1	***	***	***	***
2	5.9	55.4	12.3	0.3	***	***	***
3	***	34.8	87.0	73.9	35.5	10.2	0.4
4	***	***	0.6	25.8	64.1	80.8	25.5
5	***	***	***	***	0.4	9.0	67.9
6	***	***	***	***	***	***	6.2
7	***	***	***	***	***	***	***

Highways

Damage State	VI	VII	VIII	IX	X	XI	XII
1	93.3	18.8	2.8	1.0	***	***	***
2	6.7	61.5	27.0	13.8	1.3	0.1	***
3	***	19.7	68.8	75.4	59.0	20.5	4.6
4	***	***	1.4	9.8	39.1	65.2	50.2
5	***	***	***	***	0.6	14.2	43.4
6	***	***	***	***	***	***	1.8
7	***	***	***	***	***	***	***

Electrical Towers Less Than 100 Feet High

Damage State	VI	VII	VIII	IX	X	XI	XII
1	94.1	6.9	1.0	***	***	***	***
2	5.9	78.8	51.0	2.9	***	***	***
3	***	14.3	48.0	96.3	63.7	10.6	0.5
4	***	***	***	0.8	36.3	82.7	39.0
5	***	***	***	***	***	6.7	59.2
6	***	***	***	***	***	***	1.3
7	***	***	***	***	***	***	***

Electrical Towers More Than 100 Feet High

Damage State	VI	VII	VIII	IX	X	XI	XII
1	93.6	7.3	1.8	***	***	***	***
2	6.4	72.1	50.9	7.5	0.3	***	***
3	***	20.6	47.3	92.2	72.5	16.6	0.8
4	***	***	***	0.3	27.2	79.4	38.2
5	***	***	***	***	***	4.0	58.8
6	***	***	***	***	***	***	2.2
7	***	***	***	***	***	***	***

***Very small probability

Sample ATC-13 Shaking Damage Matrix

Damage State	Modified Mercalli Intensity Index VI	VII	VIII	IX	X	XI	XII
1	100	99.8	20.9	8.7	-	-	-
2	-	.2	**54.1**	34.7	1.3	-	-
3	-	-	17.2	36.1	7.9	.5	-
4	-	-	7.8	21.9	89.5	66.5	4.5
5	-	-	-	-	1.1	29.6	56.4
6	-	-	-	-	.2	3.3	37.9
7	-	-	-	-	-	.1	1.2

For a MMI = VIII, the largest probability is 54.1 (identified in bold); therefore the assumed damage state is damage state 2 (also in bold). The probability that the damage state or greater will occur is the sum of its probability and all the probabilities for larger damage at the MMI value of interest: (54.1 + 17.2 + 7.8) = 79.1%, or 79% for use in the subsequent analyses.

The data represented in Table 3 was developed based on assuming the facility construction methods were in California. Since California has incorporated seismic design criteria in some of their codes and standards, it raises a question as to how the data should be applied to other U.S. regions. The most direct approach would be to consider the design and construction practices at the study area in question, and to adjust the damage state predicted by Table 3 to account for differences with respect to California.

Rojahn[20] has developed a different approach. He suggests that the MMI value can be adjusted to account for the different design and construction practices. Increasing the MMI value would imply that the local practices are less conservative for earthquake considerations than those used in California. Decreasing the MMI value would imply the opposite. Figure 3 shows the U.S. divided into seismic hazard regions. The Rojahn adjustments for are presented in Table 4. He has used Figure 3 to divide the U.S. into five broad regions: California region 7; Other U.S. areas of region 7; California regions 3 to 6; Puget Sound region 5; and all other U.S. regions.

Table 4 is provided for information purposes. Data for additional lifeline components are provided in reference 20. Rojahn did not justify the selection of the Table 4 values or explain why adjustments are needed for California (recall that ATC-13 was based on assuming that it applied to California). One of the important recommended follow-on studies to the present work is to apply the present screening tool to another U.S. location. One purpose of such a study would be to examine the validity of the adjustments to MMI recommended by Rojahn.

Figure 3, MAP OF U.S. SEISMIC HAZARD REGIONS

NEHRP Seismic Map Areas (ATC, 1978; BSSC, 1988).

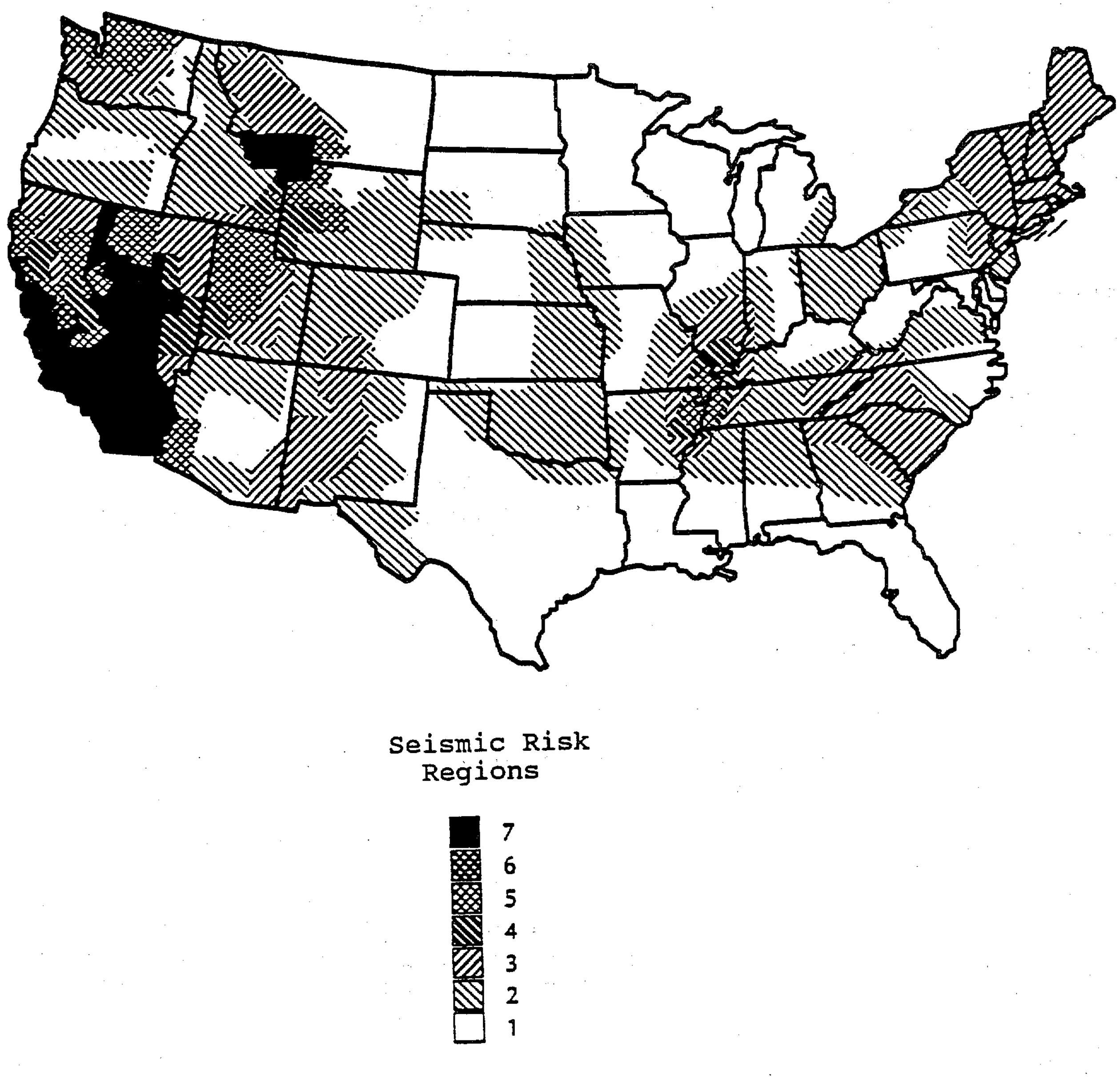


Table 4
MMI ADJUSTMENT FOR SHAKING DAMAGE EVALUATION
TO ACCOUNT FOR LOCAL CONDITIONS
(the region numbers correspond to the numbers of Figure 3)

Region	Multiple Span Bridges	Continuous Bridges	Rail beds & Highways
California, #7	0	0	0
Other area, #7	1	1	0
California, #3-6	1	1	0
Puget Sound, #5	0	1	0
Other U.S. regions	3	2 or 3	0

Region and Number	Railroad Bridges	Water Trunk Lines	Water Pipe Distribution
California, #7	-1	0	1
Other area, #7	0	0	1
California, #3-6	-1	0	1
Puget Sound, #5	0	0	1
Other U.S. regions	1	1	2

Region and Number	Electrical Towers Over 100 ft. high	Electrical Towers Less than 100 ft. high
California, #7	0	0
Other area, #7	0	0
California, #3-6	0	0
Puget Sound, #5	0	0
Other U.S. regions	0	1

Region and Number	Natural Gas Transmission	Natural Gas Distribution	Oil Pipelines
California, #7	-1	0	-1
Other area, #7	-1	0	-1
California, #3-6	-1	0	-1
Puget Sound, #5	-1	1	-1
Other U.S. regions	0	1	-1

Fault Displacement

In ATC-13, the maximum fault surface displacement, D, in meters is calculated from the equation:

$$\text{Log } D = -4.865 + 0.1719 \times M$$; where M is the earthquake magnitude

ATC-13 identifies that the fault average displacement is typically 77% of the maximum, and that 30% of the maximum displacement on the main fault is characteristic of the displacement on subsidiary faults.

The damage states for the estimated displacement are obtained from

ATC-13 Table 8.9 and are presented in Table 5.

Table 5
LIFELINE DAMAGE STATE FOR FAULT SURFACE DISPLACEMENTS, ATC-13 Table 8.9

Facility Type and Location	Damage State (% damage is given in the parentheses) For Various Values of Displacement in meters				
Displacement =	0.2 m	0.6 m	1 m	3.5 m	10 m
Subsurface Structure					
In Fault Zone	5(50)	6(80)	7(100)	7(100)	7(100)
In Drag Zone	4(20)	5(40)	5(60)	6(80)	7(100)
Surface Structures					
In Fault Zone	3(10)	4(30)	6(70)	7(100)	7(100)
In Drag Zone	0(0)	0(0)	3(2)	3(10)	4(20)

The "Fault Zone" is defined as being within 100 meters of the fault trace, the "Drag Zone" is defined as being within 100 to 200 meters of the fault trace. If lifeline components are judged to have failed because of fault displacement, then the collocation impact would be only an increase in the time to restore the lifeline to its needed level of operation (e.g., damage greater than catastrophic is not meaningful). Such time increases would be attributed to the construction activity and the need to assure that construction on one lifeline does not lead to damage on reconstructed other lifelines.

Soil Movement

Many texts separately define the impacts due to landslides and lateral spread (or liquefaction). However, they may be thought of as being part of a continuum of soil movement with the slope of the topography being a parameter that identifies whether the movement should be calculated as a landslide or a lateral spread (or liquefaction). That is the approach proposed in the present analysis method.

Landslide (landslides occur on slopes greater than 5°)

It is proposed that the historical landslides in the study area be identified and considered as potential landslide regions when the collocation evaluation is made. Keefer and Wilson[10] and Sadler and Morton[11] have identified that landslides are associated with many historical earthquakes and that shaking is one of the main triggering agents for landslides. Actual site reconnaissance visits are recommended as a means to verify the location of historical landslides for any area being studied. In the present study, a comparison of the known slides with the geologic unit map identified that many of the landslides were associated with areas where Pelona Schist is the bedrock unit. Other researchers are advised to examine the geologic sediments and rocks in the areas where they intend to evaluate collocation and to be sensitive to the location of Pelona Schist.

It is proposed that the method of Legg et. al.(12) be used to identify additional areas where landslides may occur. It is based on the sliding block model proposed by Newmark(13); Wilson & Keefer(14) have proposed a similar model. However, the Wilson and Keefer model requires using recorded accelerograms or predictions of ground acceleration while the Legg method is related to using MMI. The Legg model is the method used in ATC-13 to define the damage state and probability of damage for landslides. Also, it will be easier to apply the Legg model to other regions in the U.S.. Because of these items, the Legg method was adopted for predicting additional landslide areas.

The Legg method consists of the following basic steps:

Step 1 Solve for the "critical acceleration" of the slope for a given combination of slope angle and soil properties. A formula derived from the stability solution of an infinite slope was used by Legg and also by Wilson and Keefer, and it is provided below.

Step 2 Use the critical acceleration to enter a table of "slope failure state" versus MMI value. The table values identify the potential for the slope to move as a landslide. The tables are provided as Table 8.7 of ATC-13 and are reproduced below as Table 7.

Step 3 The slope state is related to damage state in Table 8.8 of ATC-13, which is presented below as Table 8. However, the ATC-13 Table 8.8 has been extended to more accurately account for buried lifelines, based upon expert opinion obtained during the present study.

The formula for the critical acceleration is given by:

$$a_c/g = c/(\gamma h) + \cos\theta \tan\phi - \sin\theta \text{ ; where}$$

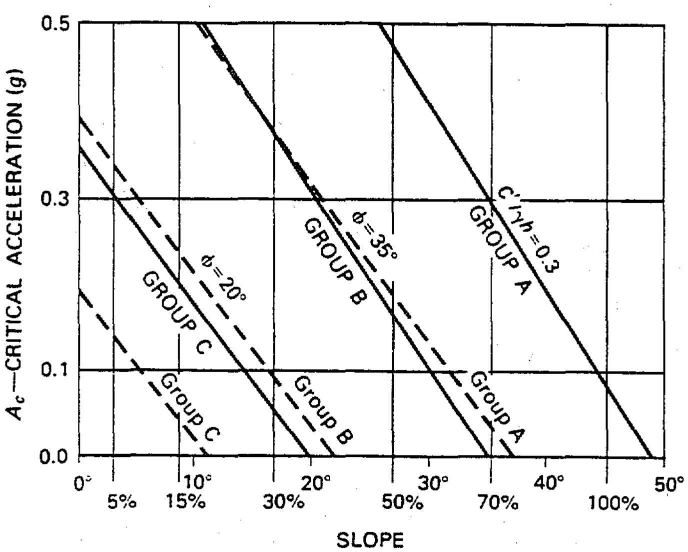
a_c = the critical acceleration, ft/sec^2
g = the gravitational constant, 32.2 ft/sec^2
c = the effective soil cohesion factor, lb/ft^2
γ = the soil density, typically 100 lb/ft^3
h = the thickness of the soil block, typically 10 ft
θ = the slope angle, degrees
ϕ = the angle of friction of the slope material, degrees
Note, this equation applies to dry slopes.

The soil parameters recommended for use are given in Table 6.

Table 6
SOIL PARAMETERS FOR CALCULATING LANDSLIDE POTENTIAL

Geologic Unit	Cohesion, c (pfs)	Shear Strength Parameters Friction Angle, (degree)
Paleozoic Rocks	300	35
Older Cenozoic Rocks	0	35
Older Alluvium	0	30
Young Alluvium at Shallow Ground Water & Pelona Schist	0	20

Wilson and Keefer[14] have also developed an analysis for saturated and dry slopes. They use a 35 degree friction angle for sands, sandstones, and crystalline rocks, and 20 degrees for clayey soils and shales. They present a graph of the critical acceleration as:



Plots of critical acceleration (A_c) versus slope steepness for three sets of lithologies: group A, strongly cemented rocks (crystalline rock and well-cemented sandstone); group B, weakly cemented rocks (sandy soil and poorly cemented sandstone); group C, argillaceous rocks (clayey soil and shale). The cohesion factor, $c'/\gamma h$, for group A assumes values of $c' = 300$ psf, $\gamma = 100$ pcf, and $h = 10$ ft. The angle of internal friction (ϕ) (peak strength, undrained conditions) is 35° for sands, sandstone, and crystalline rocks and 20° for clayey soils and shales. The solid lines depict dry slope materials, and the dashed lines depict saturation from the slide plane to the surface.

Either the Legg formula or the Wilson graph is acceptable for determining the critical acceleration, it's numeric value will be used in the Legg tables discussed below.

The appropriate soil parameters from Table 6 or other references should be identified. The formula or graph is then used to determine the value of the critical acceleration, which in turn determines the slope stability (unstable, low, moderate, high, stable, very stable) so that the ATC-13 Table 8.7 (Table 7 given below) can be used to define the state of slope failure (Table 7 uses the Legg definitions for terms of slope failure state and slope stability scale, and those definitions also are provided with the table).

Table 7
LANDSLIDE SLOPE FAILURE PROBABILITY MATRICES, ATC-13 Table 8.7

Slope Failure Probability Matrices*
(Summer Conditions)

SLOPE STABILITY: UNSTABLE, $a_c < .01\ g$

SLOPE FAILURE STATE	MMI VI	VII	VIII	IX	X	XI	XII
LIGHT	0	0	0	0	0	0	0
MODERATE	0	0	0	0	0	0	0
HEAVY	60	50	40	30	20	5	0
SEVERE	30	40	45	50	55	60	50
CATASTROPHIC	10	10	15	20	25	35	50
Σ_p	100%	100%	100%	100%	100%	100%	100%

SLOPE STABILITY: HIGH, $0.3\ g < a_c < 0.5\ g$

SLOPE FAILURE STATE	MMI VI	VII	VIII	IX	X	XI	XII
LIGHT	100	100	100	95	85	80	60
MODERATE	0	0	0	5	10	15	20
HEAVY	0	0	0	0	5	5	15
SEVERE	0	0	0	0	0	0	5
CATASTROPHIC	0	0	0	0	0	0	0
Σ_p	100%	100%	100%	100%	100%	100%	100%

SLOPE STABILITY: LOW, $.01\ g < a_c < 0.1\ g$

SLOPE FAILURE STATE	MMI VI	VII	VIII	IX	X	XI	XII
LIGHT	40	25	15	10	5	0	0
MODERATE	30	30	35	30	20	10	0
HEAVY	25	35	40	40	35	35	30
SEVERE	5	10	10	15	30	35	40
CATASTROPHIC	0	0	0	5	10	20	30
Σ_p	100%	100%	100%	100%	100%	100%	100%

SLOPE STABILITY: STABLE, $0.5\ g < a_c < 0.7\ g$

SLOPE FAILURE STATE	MMI VI	VII	VIII	IX	X	XI	XII
LIGHT	100	100	100	100	90	85	75
MODERATE	0	0	0	0	10	10	15
HEAVY	0	0	0	0	0	5	10
SEVERE	0	0	0	0	0	0	0
CATASTROPHIC	0	0	0	0	0	0	0
Σ_p	100%	100%	100%	100%	100%	100%	100%

SLOPE STABILITY: MODERATE, $0.1\ g < a_c\ 0.3\ g$

SLOPE FAILURE STATE	MMI VI	VII	VIII	IX	X	XI	XII
LIGHT	100	100	85	70	55	20	0
MODERATE	0	0	10	20	25	30	10
HEAVY	0	0	5	10	15	25	40
SEVERE	0	0	0	0	5	15	30
CATASTROPHIC	0	0	0	0	0	10	20
Σ_p	100%	100%	100%	100%	100%	100%	100%

SLOPE STABILITY: VERY STABLE, $0.7\ g < a_c$

SLOPE FAILURE STATE	MMI VI	VII	VIII	IX	X	XI	XII
LIGHT	100	100	100	100	100	90	80
MODERATE	0	0	0	0	0	10	15
HEAVY	0	0	0	0	0	0	5
SEVERE	0	0	0	0	0	0	0
CATASTROPHIC	0	0	0	0	0	0	0
Σ_p	100%	100%	100%	100%	100%	100%	100%

Table 7 (Continued)
Definitions

SLOPE FAILURE STATE SCALE	
LIGHT-	Insignificant ground movement, no apparent potential for landslide failure, ground shaking effect only. Predicted displacement less than 0.5 cm.
MODERATE-	Moderate ground failure, small cracks likely to form, cracks similar to having a lurch phenomena. Predicted displacement 0.5 to 5.0 cm.
HEAVY-	Major ground failure, moderate cracks and landslide displacements with effects similar to liquefaction or lateral spread. Predicted displacement 5.0 to 50 cm.
SEVERE-	Extreme ground failure, large cracks and landslide displacements with effects similar to large-scale fault displacement. Predicted displacement 50 to 500 cm.
CATASTROPHIC-	Total ground failure, with predicted displacement greater than 500 cm.

RELATIVE SEISMIC SLOPE STABILITY SCALE	
V -	Very stable, not likely to move under severe shaking, $a_c \geq 0.7g$.
S -	Stable, may undergo slight movement under severe shaking, $0.5g \leq a_c < 0.7g$.
H -	High, may undergo moderate movement under severe shaking, some landslides related to steep slopes, saturated conditions, and adverse dips, $0.3g \leq a_c < 0.5g$.
M -	Moderate, may undergo major movement under severe shaking or moderate movement under moderate shaking, numerous landslides, rock falls abundant, unconsolidated material deforms and fails, $0.1g \leq a_c < 0.3g$.
L -	Low, may undergo major movement under moderate shaking, abundant landslides of all types, $0.01g \leq a_c < 0.1g$.
U -	Unstable, may undergo major movement under slight shaking, most of the area and/or material falls, $a_c < 0.01g$.

cm = centimeter
g = gravitational constant

To use Table 7, it is necessary to enter it with the critical acceleration, a_c, and the MMI value. The critical acceleration value determines which sub-table is used. Within that sub-table, in the MMI column, identify the location with the peak probability. The slope failure state is read from the left-most column at the row that contains the peak probability value. The probability that the condition or worse will exist is the sum of the individual probabilities for that slope state and all worse slope state conditions. This is similar to how the shaking damage state and its probability were calculated.

Next, the slope failure status (light, moderate, heavy, severe, catastrophic) is converted to a damage state (and also a percent damage) by using ATC-13 Table 8.8 (Table 8 below). ATC-13 provides a single conversion value for all lifelines. This has been expanded in Table 8 to account for key buried lifelines. The new values were based on expert opinion obtained during the present study.

Table 8
CONVERSION OF LANDSLIDE SLOPE FAILURE STATE TO DAMAGE STATE
Damage State and (% Damage)

	ATC-13 Values	New Values Determine During This Study	
Slope Failure State	for all Lifelines	High Strength Lifelines	Low Strength Lifelines
Light	0-3 (0%)	0-2 (0%)	0-3 (0%)
Moderate	4 (15%)	3 (0%)	4 (30%)
Heavy	5 (50%)	4 (15%)	5 (60%)
Severe	6 (80%)	5 (50%)	6 (90%)
Catastrophic	7 (100%)	7 (100%)	7 (100%)

The definition of high strength buried lifelines used to determine the damage state is: continuous steel pipelines constructed according to modern quality control standards with full penetration girth welds; welds and inspection performed according to API 1104 or equivalent.

The definition of the buried lifelines which should be represented by the original ATC-13 definitions is: pipelines and conduits constructed according to modern standards with average to good workmanship, other than the high strength lifelines defined above. Lifelines in this category are expected to include electric cables, steel pipelines with welded slip joints, ductile iron pipelines, telecommunication conduits, reinforced concrete pipe including concrete steel cylinder pipe, and plastic pipelines and conduits. Also, if the high strength lifelines are oriented so that the landslide motion is expected to place them into compression, they should be analyzed in this category. Other lifelines not included in the High Strength or Low Strength definitions should be evaluated using the ATC-13 column.

The definition of low strength buried lifelines is: pipelines and conduits sensitive to ground deformation because of age, brittle materials, corrosion, and potentially weak and defective welds. Lifelines in this category include cast iron, rivetted steel, asbestos cement, and unreinforced concrete pipelines; pipelines with oxyacetylene welds; and pipelines and conduits with corrosion problems. If other non high strength buried lifelines are oriented so that they are perpendicular to the expected landslide motion (e.g., their orientation is such that they will be put into compression by the landslide), then they should be analyzed as a low strength lifeline rather than with the ATC-13 column.

Liquefaction or Lateral Spread (lateral spread occurs on slopes of 1-5°)

It is proposed that the Liquefaction Severity Index (LSI) be used to correlate the liquefaction or lateral spread damage and the probability of damage. The LSI is defined in the work of Youd and Perkins[15]. The following material was developed from expert consultive support provided during this study by Dr. T.D. O'Rourke of Cornell University[6,8,9,16].

In a manner similar to the critical acceleration defined for landslides, a critical LSI is defined in Table 9 below. The basis for its use and the LSI damage probabilities of Table 10 is the work of Harding[6] which has shown that substantial lateral spreading can be triggered at a critical acceleration, a_c, of 0.05 to 0.15 g.

Table 9
RELATIONSHIP BETWEEN LIQUEFACTION SEVERITY INDEX (LSI) AND DAMAGE STATE

Physical Lateral Ground Movement	Equivalent LSI	Damage State	Damage Condition
< 0.5 inch	< 1	3	light
0.5 to 5.0 inches	1-5	4	moderate
5 to 30 inches	5-30	5	heavy
30 to 90 inches	30-90	6	severe
> 90 inches	> 90	7	catastrophic

O'Rourke has prepared a regression analysis of the observed relationship between the MMI index and the LSI index for four earthquakes; the 1906 San Francisco, the 1964 Alaska, the 1971 San Fernando, and the 1979 Imperial Valley earthquakes. The observations identified LSI values of 5 to 100 for MMI values of V to X. The resulting regression curve (with an $r^2 = 0.68$) is:

$$LSI = 0.226 x 10^{0.255 x MMI}$$

The equation can be used to calculate the LSI number, and then Table 9 can be used to define the damage state. Graphically, the relationship between MMI and damage state is presented in Figure 4 below.

The probability that the liquefaction damage state will occur is given in Table 10. Table 10 (which replaces ATC-13 Table 8.4) applies to soil environments in which liquefaction is likely to occur under strong earthquake shaking. These environments include: active flood plains, deltas, other areas of gently sloping late Holocene fluvial deposits, and loose sandy fill below the water table (which are generally placed by end dumping or hydraulic fill methods). The table does not apply to late Pleistocene Alluvium, for which the probabilities of liquefaction are negligible for intensities equal to or less than MMI of X. Thus, the combination of the LSI equation and Table 9 (or the use of Figure 4) with Table 10 is analogous to landslide calculations for low stability material.

Table 10
PROBABILITY OF LIQUEFACTION GROUND FAILURE, PERCENT

Liquefaction Damage State	MMI Value						
	VI	VII	VIII	IX	X	XI	XII
3 - Light	75	50	20	10	0	0	0
4 - Moderate	20	30	40	25	15	10	0
5 - Heavy	5	20	30	40	25	25	20
6 - Severe	0	0	10	20	35	40	30
7 - Catastrophic	0	0	0	5	15	25	50

The new method developed during this study adds details to the level of analysis available from ATC-13. It identifies a range of damage from light to catastrophic (compared to the assumed catastrophic levels of ATC-13) and a full range of probabilities that the damage state will occur. Since it is based on observed liquefaction damage from California earthquakes, additional evaluation of the recommended approach at other U.S. locations is warranted.

Highway and Railroad Bridges

The ATC-13 shaking intensity matrices (Table 3) identify three broad classes for bridges: multiple simple span bridges, continuous and multiple span bridges, and long span or major bridges. It is difficult to fit every railroad and highway bridge into one of these broad classifications. One example of how owner-supplied information can be used to improve upon the direct use of the ATC-13 guidance is found in the methods of the California Department of Transportation[17,18,19] (CALTRANS). CALTRANS has a method to identify the priority for performing retrofits to their bridges to reduce their vulnerability to earthquakes. This improved data was

LIQUEFACTION INDUCED DAMAGE

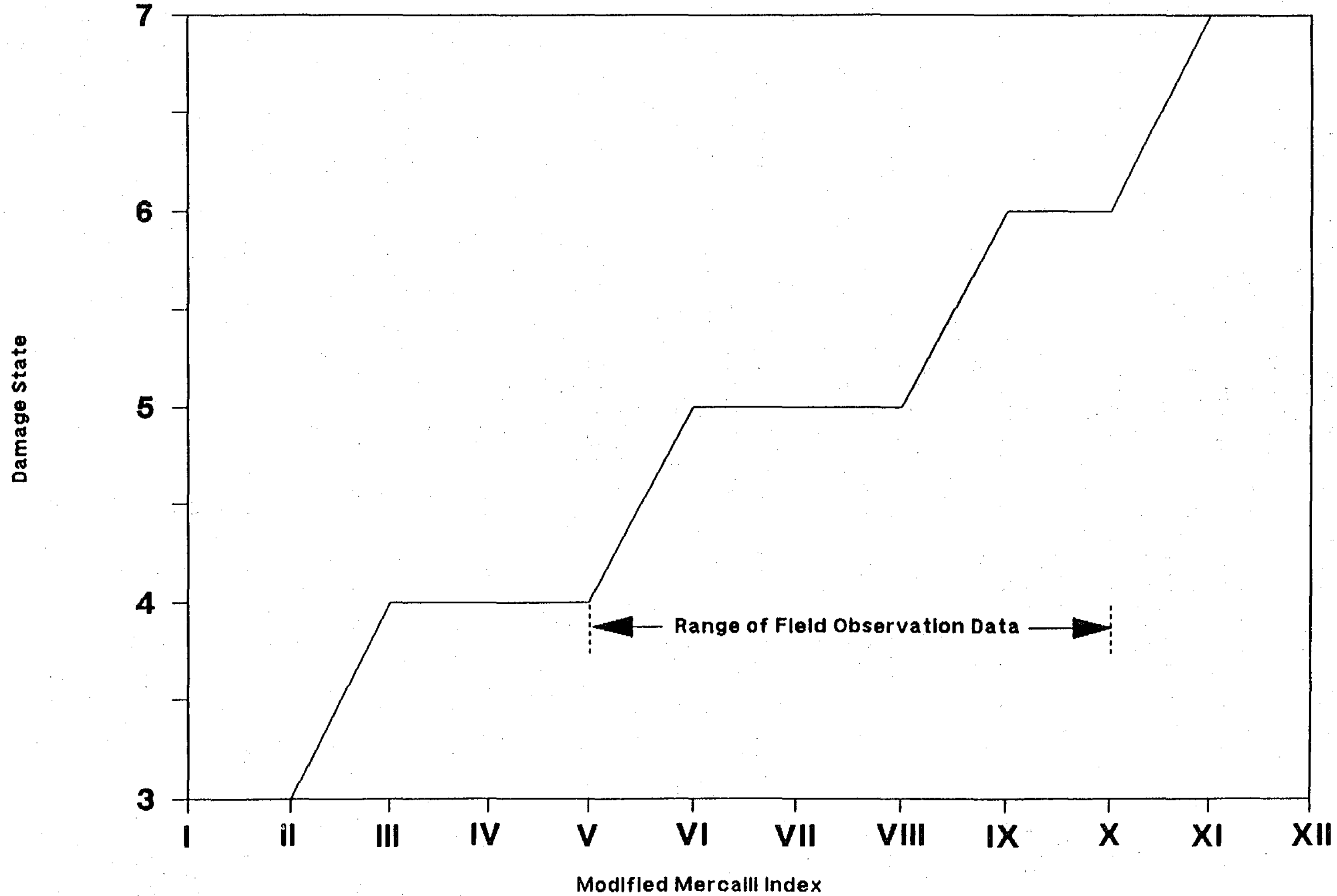


Figure 4

integrated with the ATC-13 data to provide more discrimination capabilities for evaluating railroad and highway bridges. The resulting procedures (described below) are fully applicable to locations outside of California if the needed data on the individual bridges are known. The CALTRANS method includes factors, such as traffic loading and detour routes, that are important for making decisions about whether to spend money to retrofit a bridge, but they are not important for determining the damage state of the bridge. However, other factors, such as the bridge sub and superstructure, the design codes used, and the bridge geometry can be related directly to the ability of the bridge to resist earthquake damage.

The method being proposed in this report calculates a parameter that can be used to adjust the damage state value for shaking as determined by the ATC-13 matrices (Table 3 of this report). The evaluation is based on starting with the ATC-13 shaking probability matrix for Continuous and Multiple Span Bridges. The procedures discussed above on how to use Table 3 to define the damage state and the probability that the damage state or greater will occur are used to calculate a tentative damage state. A bridge vulnerability index then is calculated and used to determine if the tentative damage state should be changed (the probability is not changed). The decision to adjust the Table 3 tentative damage state value is based on the numeric values identified below in Table 11 (high values of the Bridge Vulnerability Index mean that the damage will be more severe than that predicted by Table 3).

Table 11
RELATIONSHIP OF BRIDGE VULNERABILITY INDEX TO BRIDGE DAMAGE STATE

Bridge Vulnerability Index Value	Change to Table 3 Continuous & Multiple Span Bridge Damage State Value
0.0 - 0.2	Lower the Damage State by two increments
0.2 - 0.4	Lower the Damage State by one increment
0.4 - 0.6	No Change
0.6 - 0.8	Increase the Damage State by one increment
0.8 - 1.0	Increase the Damage State by two increments

The numeric value of the Bridge Vulnerability Index is calculated by multiplying a Raw Score by a Multiplying Factor (in the CALTRANS' method, the terms were weighting factor and pre-weighting factor, respectfully). The Raw Score is assigned by the importance of the bridge factor being evaluated, the Multiplying Factor is a weighting scale that determines how earthquake resistant the Raw Score items is. Table 12 presents the numeric values of the Raw Score and the Multiplying Factors.

There are seven categories that are analyzed: 1) abutments; 2) piers; 3) soil type; 4) superstructure type; 5) design code or specification used; 6) bridge height; and 7) bridge skew and curvature. A separate number (the raw score times the multiplying factor) is calculated for each of the seven categories and then the individual numbers are summed. The sum is divided by 100 to give the total Bridge Vulnerability Index value.

In applying the incremental change to a tentative damage state from Table 3, if this results in a damage state less than 1 or greater than 7 use those limit values. Damage states for long span (length greater than 400 feet) and major bridges may be estimated using this procedure, but it is recommended that such structures be subjected to special studies whenever possible. It is emphasized that the above Bridge Vulnerability Index is for shaking damage. Special conditions, such as liquefaction, require additional analysis.

The analysis factors required to enter Table 12 can be obtained from the general design drawings of the bridge or by field reconnaissance. Some assumptions may have to be made with respect to foundation design in the latter case.

Railway bridges have proved to be somewhat more resistant to ground shaking than highway bridges, in spite of the fact that the American Railway Engineering Association (AREA) specifications make no specific recommendations with regard to earthquake forces. This is probably due to the fact that railroad brides have an allowance for lateral loads (originally, the allowance was to account for the loads produced by steam locomotives). Prior to 1935, this allowance was 5% of the live load (typically based on a Cooper E60 engine, or about 852,000 lbs. on a 109 ft. span), but not more than 400 lbs. per foot of track. In 1935, this was changed to provide for a lateral load of 20,000 lbs. applied at the top of the rail at any point in the span. In 1950, AREA provided for higher allowable stresses, so that the allowance became somewhat less conservative. The multiplying factors of Table 12 for railroad bridges reflects these facts.

Table 12
BRIDGE VULNERABILITY INDEX FOR EARTHQUAKE SHAKING DAMAGE

Bridge Element	Raw Score	Multiplying Factor Criteria	Multiplying Factor Value
SUBSTRUCTURE			
Abutments	10	Integral with pile foundation	0.0
		Integral with spread footing	0.5
		Hinge seat with restraints	0.6
		Hinge seat, all other types	1.0
Piers	15	wall	0.2
		multiple column bent	0.5
		single column bent	1.0

Note, if a spread footing foundation is used, add 0.2 to the pier multiplying factor, if the columns have been reinforced to recent seismic codes, subtract 0.3 from the pier multiplying factor.

Bridge Element	Raw Score	Multiplying Factor Criteria	Multiplying Factor Value
Soil Type	15	Rock or soil with bearing of more than 4 tons/ft^2	0.0
		Soil with bearing of 2 - 4 tons/ft^2	0.1
		Soil with bearing of less than 2 tons/ft^2	0.5
SUPERSTRUCTURE			
Type	20	Highway Bridges	
		Simple span, box or slab	0.0
		Single span, arches, reinforced concrete or well constructed masonry	0.1
		Simple span, steel or concrete beams	0.5
		Simple span, steel truss	0.5
		Multiple spans, continuous with no hinges	0.0
		Multiple spans, continuous with 1 hinge	0.5
		Multiple spans, simple beams	1.0
		Multiple spans, continuous with 2 or or more hinges	1.0
		Railroad Bridges	
		Simple spans, steel with full truss	0.3
		Simple spans, deck or half truss	0.4
		Simple spans, steel or concrete ballasted	0.5
		Simple spans, steel or concrete beams	1.0
		Multiple spans, fully continuous	0.0
		Multiple spans, simple beams	1.0
		Multiple spans, continuous with hinges	1.0

Note, for both highway and railroad bridges with hinges, subtract 0.4 from the multiplying factor if restrainers have been added. Subtract an additional 0.3 if the columns have been reinforced to resist earthquake forces.

Table 12 (Continued)
BRIDGE VULNERABILITY INDEX FOR EARTHQUAKE SHAKING DAMAGE

Bridge Element	Raw Score	Multiplying Factor Criteria	Multiplying Factor Value
DESIGN CODE OR SPECIFICATION			
Code used	20	Highways	
		CALTRANS* after 1978 or AASHTO* after 1987	0.0
		CALTRANS between 1972 and 1978	0.2
		CALTRANS prior to 1972 and AASHTO prior to 1950	0.5
		AASHTO from 1950 to 1987	1.0

Note, AASHTO, from 1950 to 1987, leaves the earthquake considerations to the States. If it is known that the State has no such consideration, use 2.0 as the Multiplying Factor value.

		Railroads	
		AREA* from 1935 to 1950	0.5
		AREA from 1950 to present	0.7
		AREA prior to 1935	0.8

Note, for the condition of bridge, modify the design code or specification Multiplying Factor by adding the following to the factor:

		Good or fair condition	0.0
		Poor condition	0.2
GEOMETRY			
Height	10	Less than 5 feet	0.2
		5 to 15 feet	0.7
		15 to 25 feet	0.9
		25 feet and greater	1.0
Skew* and curvature	10	Skew less than 20° and radius greater than 1000 ft.	0.0
		Skew 20°-40° and/or radius greater than 500 ft.	0.1
		Skew greater than 40° and/or radius less than 500 feet	0.4

Key *
AASHTO, American Association of State Highway & Transportation Officials
AREA, American Railroad Engineering Association
CALTRANS, California Department of Transportation
Skew is defined as the angle that abutments and piers make with respect to the normal to the highway (or railway) alignment. That is, when the plane of the abutment or pier is aligned parallel to the normal to the road (or rail bed) alignment, the skew is 0°.

Times to Restore the Lifeline to its Needed Service

Once the lifeline components of interest have been identified and the damage state and probability that the damage condition or worse will occur have been calculated from the above tables and formulas, the time to restore the lifeline component or segment from the total calculated damage state to the operating level needed has to be determined.

The restoration time is a combination of the time to repair the lifeline segment or component assuming all the equipment, material, and personnel are available at the damage site, plus the access time to get the equipment and material to the damage site, plus the delay time needed to obtain the equipment and material required for making the repair. The way to calculate these items is given next.

Repair Time to restore the damaged lifeline to service

With the damage state known, the time to repair the lifeline component or segment (assuming the equipment and material are at the damage location) can be calculated from Table 9.11 of ATC-13. The key information of Table 9.11 is provided below as Table 13. If intermediate operating conditions (e.g., repair to less than 100% capacity) are acceptable, the intermediate repair times of the ATC-13 tables can be used or the plots of those tables provided by Rojahn[20] can be used to estimate such intermediate condition repair times. The newer curves by Rojahn are curve fits of the data of ATC-13[2], thus they are not exact replications of the data. But they may be more convenient to use since they relate the repair time to MMI instead of to the damage state as is done in ATC-13. Also, if there is concern about the magnitude of the repair time estimated, Table I.1 of Appendix I of ATC-13 can be used to determine the range of repair times identified by the experts that prepared Table 9.11. It is important to recognize that the actual repair time is not used directly to estimate the impact of collocation on the vulnerability of lifelines to earthquakes (as will be shown below).

Eleven of the more important repair tables are presented in Table 13 (some of the tables were adjusted from the ATC-13 values to account for expert opinion obtained during the present study). To make a specific estimate of lifeline repair time, enter the proper lifeline table at the row that identifies the damage state and move to the right until the correct lifeline column is encountered. Then read the time, in days, required to restore the lifeline to full capacity from that damage state. The ATC-13 lifelines of interest are: 18c-petroleum transmission pipelines, 25a-highway major bridges, 25c-highway conventional bridges, 25d-freeways and highways, 26a-railroad bridges, 26c-railroad roadbeds, 29b-electrical transmission towers, 30f-water trunk lines, 31a-sewer lines, 32a-natural gas transmission lines, and 32d-natural gas distribution lines. It should be recalled, however, that better estimates of repair time are probably available from the individual lifeline owners, as they may have site specific conditions included in their estimates.

Table 13
ESTIMATED LIFELINE REPAIR TIMES TO 100% OPERATING CAPACITY
ATC-13 Table 9.11
(Times in Days)

Damage State	Highway Bed	Railroad Bed**	Highway** Conventional Bridge	Highway Major Bridge	Railroad Bridge	Water Trunk Line
1*	1	1	1	1	1	1
2	1	1	1	2	1	2
3	7	2	8	7	8	3
4	41	11	84	141	58	10
5	147	41	303	392	213	25
6	292	82	686	845	468	74
7	437	120	752	947	606	156

Damage State	Natural Gas** Distribution & Petroleum Lines	Natural Gas Transmission Pipelines	Fiber Optic** Conduits	Electrical Transmission Towers	Sewer Lines
1*	1	1	1	1	1
2	1	1	1	1	3
3	3	3	1	2	5
4	6	11	3	17	18
5	19	25	10	49	63
6	44	44	24	82	102
7	55	75	30	127	141

* Damage State 1 has a 1 day allowance to allow for inspection to determine the actual damage state that exists at the lifeline

** These values were determined by expert opinion during this study

Access Time to get the equipment and material to the damage site

Next it is necessary to estimate the time to get the equipment and repair material to the site. This time is the time to get construction equipment and material to the damage site, and it should not be confused with the time it would take to get general population traffic to the site or with the time it would take for repair crews to get to the damage site. In many situations, and especially for lifelines such as pipelines, fiber optics, and electrical transmission towers, most of the necessary equipment and material can be driven to the damage location either along the highways, unpaved access roads, or cross country if the land is dry and accessible. In some of the more rugged regions they can be helicoptered to the site. An exception would be if wet ground or large water bodies must be negotiated. Thus, in general, for those lifelines the access time is one or two days, depending upon the location of the segment or component of the lifeline system being examined. If access along the highway is required it should be calculated as described below for the railroads and the highways.

For many of the railroad or highway components and segments, the access will have to be along the railroad or highway itself because of the size and weight of the material and equipment that is required. In such cases, it will be necessary to estimate the repair times for damage along the route prior to the location being studied. The individual repair times must then be added for each disruption that occurs before the location being studied to obtain a total estimated access time. Alternatively, detours can be used to calculate a "by pass" time estimate.

Equipment and Material Time to have those items available

For many of the lifelines, the owners have their own operating equipment and have prepositioned repair material along their lifeline routes. When they don't have suitable repair equipment in their operating stock, they may have existing agreements with other firms to provide such equipment during emergencies. Frequently, utility lifeline owners have reciprocal agreements with other utilities to provide personnel and equipment during emergency periods. This preplanning can decrease the time it takes to have equipment and repair material available to transport to the damage location.

The problem of material availability can be pronounced for railway and highway bridge repairs. In those cases, the time required to fabricate off site the needed components must be accounted for in the estimation of the delays in having equipment and material available.

In almost all cases, it can be assumed that the equipment will not be available during the emergency phase of the earthquake, since it will be diverted to life-saving duty at that time. However, prior earthquake response experience indicates that most equipment and needed material will be made available within one or two days.

4.3 Collocation Analysis

Section 4.2 presented a number of analysis methods that can be used to determine the damage state, the probability that the damage state or worse will occur, and the estimated restoration time to return each lifeline component or segment to its needed service level.

In the collocation analysis activities, a collocation damage scenario is developed and the unknown conditions (either damage state, probability of damage, restoration time, or any combination of those items) are recalculated for the assumed collocation damage scenario using the methods of Section 4.2. The collocation damage scenario should be based on the knowledge of how the individual lifelines would have responded if they had be the only lifeline at the collocation point, the estimate of the types of impacts that one lifeline failure could impose on another nearby lifeline, and the zone of influence that one lifeline has.

This process requires that technical judgements be applied, based on knowing the expected damage states of the collocated lifelines, the seismic and geologic conditions, information about the lifelines themselves (such information as the design conditions, construction history, repair and maintenance history, and other pertinent facts), and other lessons learned from prior earthquakes. It will be important to obtain as much information from the lifeline owners as possible to help guide the collocation damage scenario analyses.

It is also important to recognize that there is a zone of influence, beyond which the impact of one lifeline on another would be negligible. During this study, expert opinion was used to estimate the appropriate radii of influence zones for the lifelines found in the Cajon Pass. The results are given in Table 14.

Care must be taken to differentiate between the zone of influence and the actual influence or damage caused. For example, the zone of influence of a failed dam is based on the path of the water that spills past the dam. It includes the actual pathway and the area that the water would inundate. The actual impact of the failed dam could be erosion of foundations of other lifelines (thereby causing them to collapse) or the flooding of them (perhaps restricting their ability to function). There may be no influence on one lifeline, while the impact on another could be pronounced. Some of the impacts may be subtle. For example, a failed communication lifeline may have no immediate impact on the physical state or condition of other nearby lifelines. Its impact, however, could be tied to increasing the restoration time of nearby lifelines due to the difficulty of maintaining communications with the repair personnel. In the present context of lifeline vulnerability, the impact of one lifeline on a collocated or nearby lifeline can be the damage state, the probability of damage, or the restoration of service time. Other impacts, although real, have no way to be accounted for in the analysis method.

Although the values in Table 14 are considered appropriate for the semi-desert region of the Cajon Pass, California, for which they were prepared, it will be important to validate these values when the lifeline zones of influence are evaluated for other at-risk or collocation conditions.

Table 14
LIFELINE ZONES OF PHYSICAL INFLUENCE

Liquid Fuel Pipeline -	The drainage path and catchment area for any liquids spilled; two times the pipe burial depth for any soil cratering impacts due to pipeline ruptures; 100 feet if explosion impacts are estimated; ground erosion paths for liquids spilled; and the burn path if fires are estimated.
Natural Gas Pipeline -	Two times the burial depth for any soil cratering impacts due to pipeline ruptures; 100 feet if explosion impacts are estimated; and the burn path if fires are estimated.
Fiber Optic Cables -	Zero feet (e.g., no physical impact on other lifelines).
Roadways -	40 feet from the road edge; a possible ignition source for fuel lifelines.
Railroads -	40 feet from the track edge; a possible ignition source for fuel lifelines.
Overhead Electrical - Transmission Towers & Power Lines	A radius equal to the height of the tower for physical contact; a possible source of ignition for fuel lifelines.
Bridges -	For an area centered on the bridge, twice the length of the bridge and 40 feet on either side of the bridge.
Dams, Reservoirs & - Canals	The drainage path and inundation areas for the spilled water.
Water & Sewer Lines -	The erosion area downstream of the break (sewers only if they are pressurized); the catchment area for the spilled fluids.

It is anticipated, but not required, that collocation impact scenarios will follow the following general guidance.

Impacts on Damage State

One of the easier direct impacts to hypothesize will be that the collocation conditions will lead to an increase in the damage state of one or both of the collocated lifelines (if there are more than two collocated lifelines this applies to all of them). It is easy to understand the damage state, as it relates to a physical condition. Because the individual lifeline damage states assuming no collocation are known, those values can be used to help understand how the lifeline could impact another nearby lifeline. If, for example, light damage of a pipeline had been calculated, it would be expected to cause no direct change in the damage state of a nearby bridge. However, if the bridge had been estimated to collapse, it would be reasonable to estimate that within the bridge's zone of influence it would lead to failure of the pipeline (this example also illustrates that the impacts are not necessarily reciprocal).

As another example of how collocation impacts on damage state can be estimated, consider the condition of a pipeline and a fiber optic conduit hung from a bridge. The earthquake vibration may not be enough to cause serious damage to the bridge or to the pipeline or conduit if they were not collocated with each other. However, the vibrations may cause the anchors holding the heavy pipeline to the bridge to fail. As the pipeline sags (but does not fail) it could fall onto the lower conduit, causing it to fail. The collocation damage state hypothesis would then be: no impact on the bridge; a small increase in damage state of the pipeline to account for the work required to rehang the pipeline; and catastrophic failure of the fiber optic conduit.

Special attention should be given to the collocation of fuel carrying lifelines with other lifelines that have the ability to provide an ignition source. The resulting fire and/or explosion could lead to significant collocation damage. Similarly, broken pipelines which eject fluids could lead to foundation erosion problems that would result in increased damage to nearby lifelines.

Impacts on Probability of Damage

The probability of damage does not directly enter into the calculation of the damage state level or the time to repair the damage. It is, as will be discussed below, a very important item for determining the key result of the collocation analysis, the probable incremental change in restoration of service time.

There are several ways to estimate the change in the probability that damage will occur, none are exact and there are no statistics available from the literature on earthquakes. However, there are some insights available to guide the analysts.

If the probabilities for two lifelines, assuming no collocation conditions, are P1 and P2, they represent an upper bound on the probability that a collocation damage would occur. For example, if the probability that lifeline 1 would fail is P1, and it is known that if lifeline 1 fails it will cause, with a 100% probability, damage to lifeline 2, then the probability that lifeline 2 receives collocation damage is also P1 (e.g., P1 x 100%). Similarly, the upper bound on the probability that lifeline 2 has damaged lifeline 1 is P2.

As a practical matter, the collocation damage likely will be less, since there is seldom a 100% chance that the collocation damage scenario will occur. A useful measure of the probability that the collocation event has occurred is the product of the two probabilities that the single independent events that were used to develop the collocation scenario have occurred (the independent events are the estimate of the damage state of each lifeline assuming there was no collocation). In the present case, that is found by multiplying P1 x P2. The product can be interpreted as follows. It represents the increase in probability that the two independent lifeline damages will occur during the same initiating event. If both events must occur before the collocation damage scenario can take place, then it is a measure of the probability of the collocation damage scenario.

The actual probability that the collocation event will occur should be a number between the numerical limits of P1 and (P1 x P2) for having lifeline 1 cause additional damage to lifeline 2, and P2 and (P2 x P1) for having lifeline 2 cause additional damage to lifeline 1. It is recommended that for calculational purposes, the product P1 x P2 be used to characterize the hypothesized collocation damage scenario.

Impacts on Time to Restore Lifeline Service

As discussed above, the time to restore lifeline service is composed of the sum of the time to repair the lifeline damage, the time to access the damage site with equipment and material, and the time to obtain the equipment and material.

The hypothesized collocation damage scenario does not have to assume a repair time. Once the collocation damage state is known, the repair time can be obtained from Table 13.

However, it is reasonable to include in the collocation damage scenario impacts on accessibility to the damage site, which has the impact of increasing the overall restoration of service time estimate. In fact, this is probably one of the more significant aspects of the collocation damage scenario, e.g., the estimation of the additional direct delays that will be incurred because of the collocation of the lifelines. The greater the level of damage estimated for each of the separate lifelines, assuming that there is no collocation, the greater the anticipated delays that will result from their actually being collocated.

The following are offered as possible examples of how collocation could create access delays that would increase the time to restore the lifeline to service. General congestion at the collocation location because there are multiple lifelines could delay the start of repair work on a lifeline. Concern over the possibility of leaking fuel may cause all work to be delayed until it can be confirmed that it is safe to have workers in the area. Spilled liquid fuels may have to be treated and/or removed before construction vehicles and welding (which could provide an ignition source for fuel vapors) would be allowed.

Work on a pipeline buried next to a railroad may be delayed while debris about and on the railroad is removed by heavy equipment. Then, because of the weight of the debris and/or the heavy equipment, the entire pipeline may have to be exposed and inspected before it is allowed to return to service. Often, power transmission towers are replaced with temporary towers while repair work on the damaged tower is performed. However, the use of a temporary tower may limit the access of pipeline and transportation lifeline repair crews because of the increased potential for electrocution if heavy equipment is operated near the temporary tower. Fires at collocation locations can increase the time required to inspect the nearby lifelines to determine the extent, if any, of damage caused by the fire. Water inundation can cause delays until the water is drained and the surrounding ground dries to a condition that allows the repair equipment and material to be delivered to the damage site. Major damage to a lifeline may result in a regulatory review about the suitability of rebuilding (or repairing) the lifeline. While the regulatory review is underway the repair on the lifeline may be delayed.

In summary, a collocation damage scenario must be developed, based on the knowledge of the lifelines and their anticipated damage state if they had been isolated or non-collocated. This will result in the estimation of a new damage state, new access times, or combinations of those items. With the damage state known, a new repair time is calculated, and the repair time and access time are used to determine the new time to restore service.

4.4 Interpretation of the Results

This is the activity that brings together all of the previous analyses.

The most appropriate measure of the impact of lifeline collocation because of an earthquake was judged to be the most probable incremental increase in the time to restore the lifeline to its needed service level. The restoration of service time is a broad measure of the impact of lifeline damage on personnel, equipment, and material resources, it does not measure the impact that the loss of the lifeline has on the community that was relying upon it. The difference between the restoration of service time assuming collocation impacts and the shorter restoration time found by assuming no collocation impacts gives the incremental impact that collocation has caused to service restoration. The incremental time impact is a better measure of collocation impacts as compared to the estimated total time to restore service, because any biases in the estimation procedures tend to be canceled by the subtraction process.

It is important to multiply the incremental change in restoration time by the probability that the collocation damage has occurred. This recognizes the uncertainties in the data base and analysis methods provided in Section 4.2, and it also recognizes that in actual earthquakes there is a real probability that a given level of damage will occur, or conversely, will not occur. The product, incremental change in restoration time multiplied by probability, identifies the most probable incremental change in restoration time.

There are two ways to use the final measure:

1) the most probable incremental change in restoration time can be considered at a specific collocation site to evaluate the impacts at that site. This will provide an insight on the vulnerabilities that occur when specific types of lifelines are collocated at at-risk locations. That is, this type of information will help identify which lifeline types or which lifeline design or construction practices, when collocated with other lifelines, lead to the greatest increases to the other lifelines' level of vulnerability.

2) the most probable incremental change in restoration time can be summed along the route of a given lifeline to provide an insight on the impacts that the specific lifeline route has had on the vulnerability of the lifeline. This type of information can be used to help identify undesirable routing decisions.

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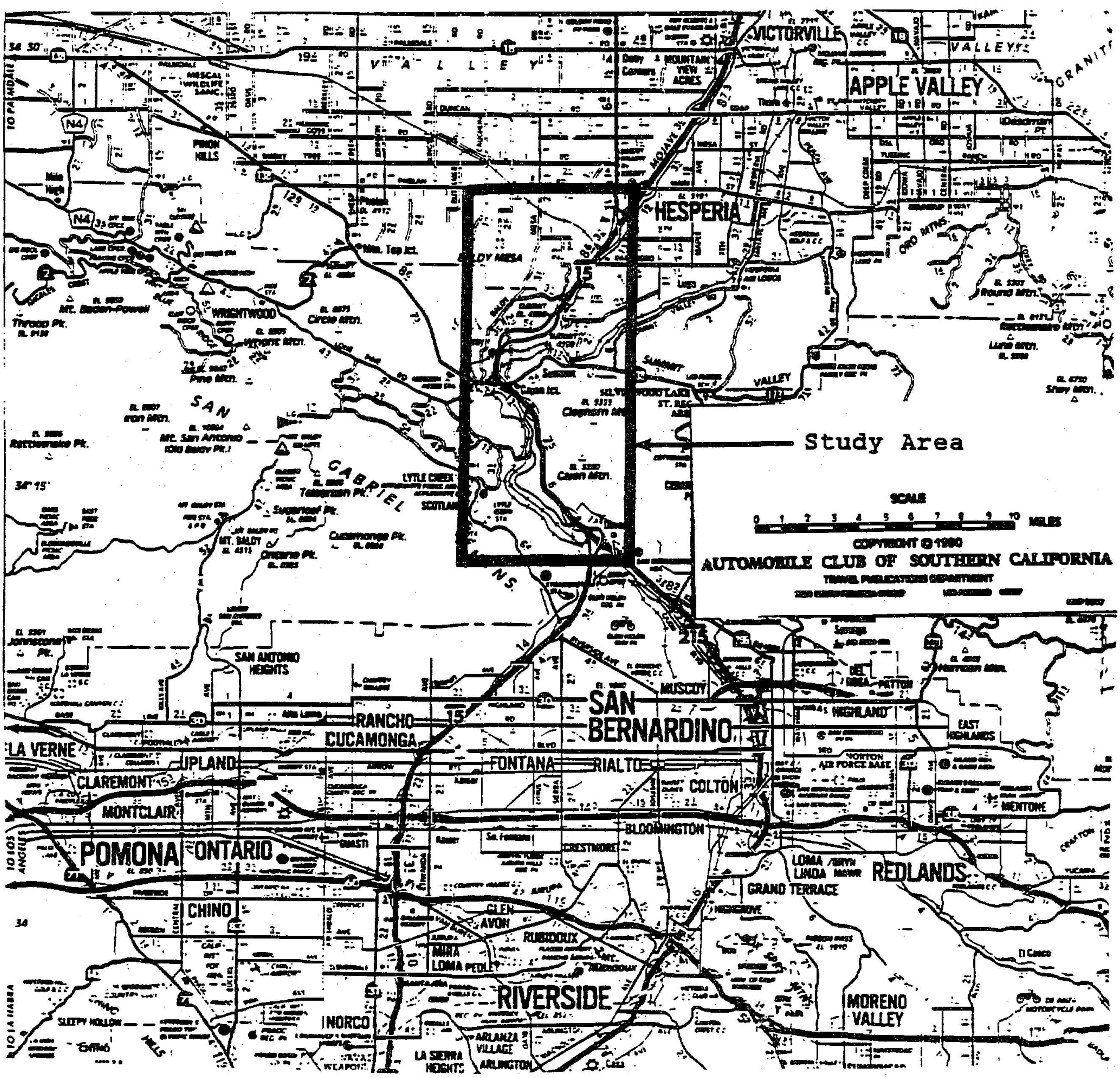
5.0 APPLICATION THE METHOD TO CAJON PASS

5.1 Data Acquisition

The following material demonstrates the application of the analysis method described in Section 4.0. The first step of the process is to assemble the data base that describes the lifelines and their routes in the study area as well as the geologic and seismic situation. The earlier Cajon Pass study[1] provides most of the needed information. It should be consulted for specifics about each lifeline and when it was installed.

Figure 5 shows the Cajon Pass study area and its relationship to other cities in California. It is used with the permission of the Automobile Club of Southern California (it is copied from the San Bernardino County and Las Vegas Area map). It shows that the Cajon Pass canyon (which is about 10 miles northeast of San Bernardino) is a natural access route between the San Gabriel Mountains to the

Figure 5, MAP OF THE GENERAL LOCATION OF THE CAJON PASS STUDY AREA



west and the San Bernardino Mountains to the east. The Pass connects the Los Angles Basin in the south to the high desert regions to the north. The City of San Bernardino is about 10 miles southeast of the mouth of the Pass.

U.S. Geological Survey quadrangle maps (7.5 minute series topographic maps published in 1988) were used to obtain more detail and to develop a plan for a site survey. The site survey was then conducted. It identified additional lifelines that were not identified on the 7.5 minute quadrangle maps, which emphasizes the need to conduct actual site surveys to validate the published information on lifeline systems. With the map and site visit information as a background, the individual lifeline owners were contacted and meetings were held with their staff to obtain more details on the location, capacity, design basis, operating and maintenance history, and emergency response systems in place for each lifeline. The Cajon Pass site was revisited to validate our understanding of the actual siting conditions, and in some cases this led to additional visits and discussions with the lifeline owners to resolve questions. This emphasis on the lifeline data acquisition and validation is very important, as there are over 100 discrete locations (which include over 250 separate combinations of collocated lifeline components) in the Cajon Pass study area where different lifeline components are in close enough proximity that it was necessary to evaluate their potential for collocation impacts.

Figure 6 is a plot of the communication, electrical power transmission, natural gas pipelines, petroleum products pipelines, railroad, and highway lifelines overlaid upon the U.S. Geological Survey's quadrangle map of the study area. Figure 6 shows several important items. First, the Pass is crowded with the lifelines traveling in a general north-south orientation through the middle of the study area. Second, the lifelines are clearly routed in a utility corridor. Since the bed of the Pass varies from about 0.5 miles near Blue Cut (which is located in about the center of the figure) to over several miles wide at most other regions, topology requirements alone would not require the observed congestion. The conclusion reached was that routing criteria such as aesthetic, cost, land use, and environmental considerations have had the controlling impact on the lifeline routing decisions.

There are especially congested areas near the intersection of Highways I-15 and I-215 in the southeast corner of the study area, near Blue Cut in the center portion of the study areas, and south and separately north of the intersection of Highway I-15 and State Highway 138. In addition, there are crowded areas for several of the lifeline systems, for example, near the railroad summit of Cajon Pass where natural gas pipelines, fiber optic lines, and the railroads are closely located. Also in the northern portion of the study area it is crowded where the two petroleum product pipelines and two fiber optic conduits parallel one set of high voltage power lines and also along Baldy Mesa Road where the two petroleum

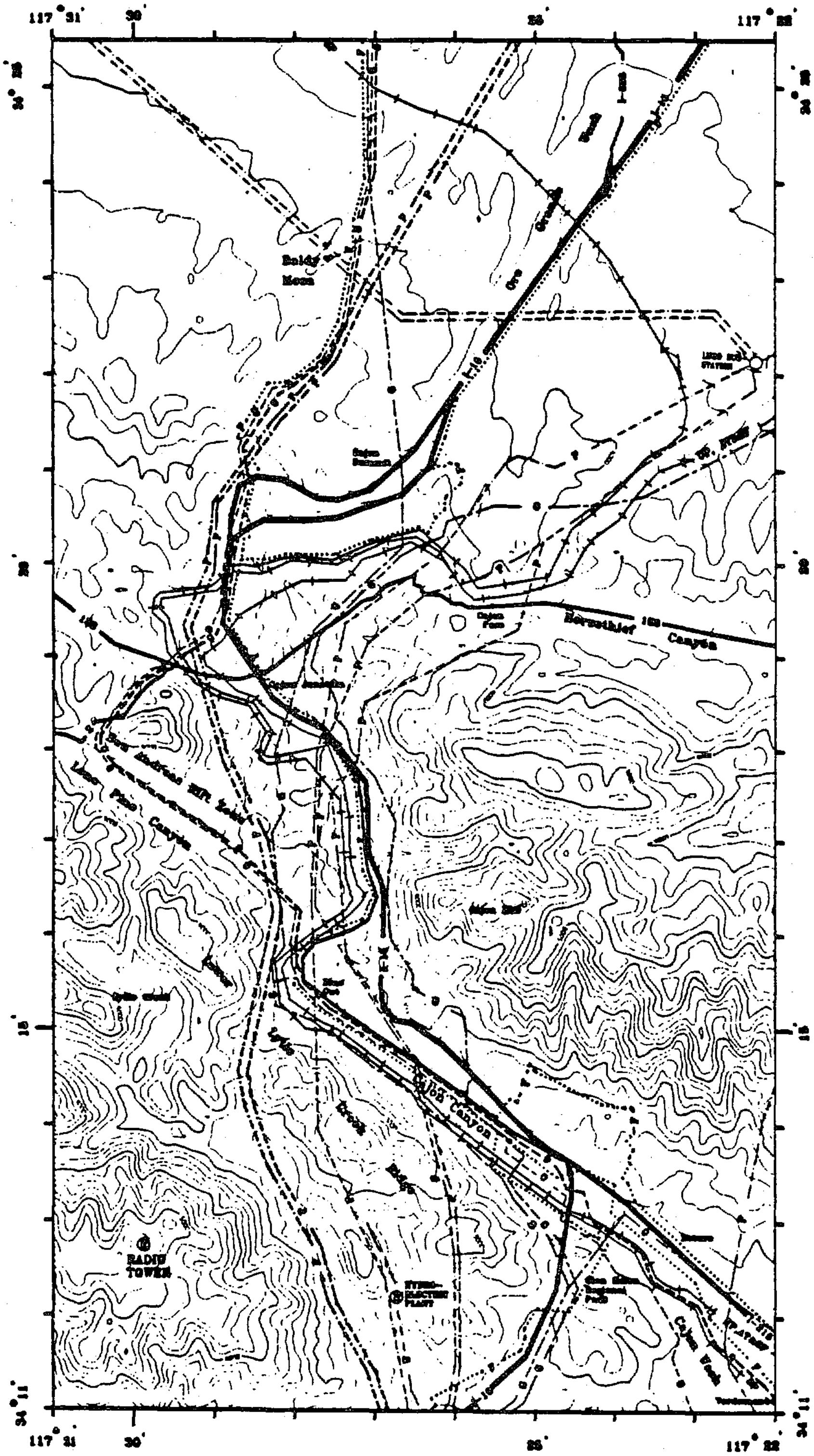
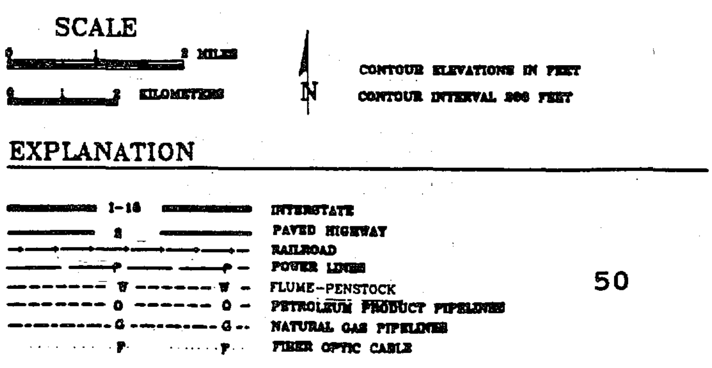


Figure 6, A COMPOSITE OF THE LIFELINE ROUTES AT CAJON PASS



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product pipelines, the fiber optic conduits, and a natural gas pipeline all are routed alongside of the road bed. The two petroleum product pipelines, a natural gas pipeline, and two high voltage power lines cross the San Andreas fault in Lone Pine Canyon at approximately the same region. The unfortunate routing for several miles of the petroleum products pipelines along the San Andreas fault's rift zone does not enter into the current study since there are no collocated lifelines of interest along that route. Finally, there are collocated railroad lines, power lines, a natural gas pipeline, the petroleum products pipelines, and the fiber optic conduits parallel to I-15 between the I-15/I-215 interchange and Blue Cut.

Figure 7 is another composite map of Cajon Pass. Each of the 101 collocations that were analyzed during this study are shown on this figure. Within those 101 locations, over 250 individual collocations occurred. This emphasizes how siting decisions have resulted in crowded collocation conditions, even though there is sufficient space to avoid most of them. Although there are several broad grouping of lifeline intersections, it is clear that they occur throughout the entire length of the study area.

The seismic and geologic information was also obtained during the data acquisition phase of the study. A sensitivity evaluation of six postulated earthquake events was performed to guide the selection of the event for use in the study. Other[2,3] studies were consulted to help select the earthquake events. The six events were:

1) The 1857 Ft. Tejon earthquake on the San Andreas fault. This was 300 km long fault with a magnitude 8.3 earthquake, and with the southern edge of the surface displacement located just north and west of Blue Cut.

2) An earthquake on the southern segment of the San Andreas fault. This was a 200 km long fault of 7.8 magnitude. The northern edge of the surface displacement was placed just north and west of Blue Cut.

3) An earthquake similar to event 1, except that the southern extreme of the surface displacement was moved about five mile further east into the study region.

4) An earthquake similar to event 1, except that the length of the fault was reduced to 105 km. This resulted in a 7.7 magnitude earthquake.

5) An earthquake similar to event 1, except that it was centered about the Cajon Pass. This resulted in a 8.3 magnitude earthquake.

6) A earthquake of 94 km length, but placed on the San Jacinto fault. This resulted in a 7.5 magnitude earthquake.

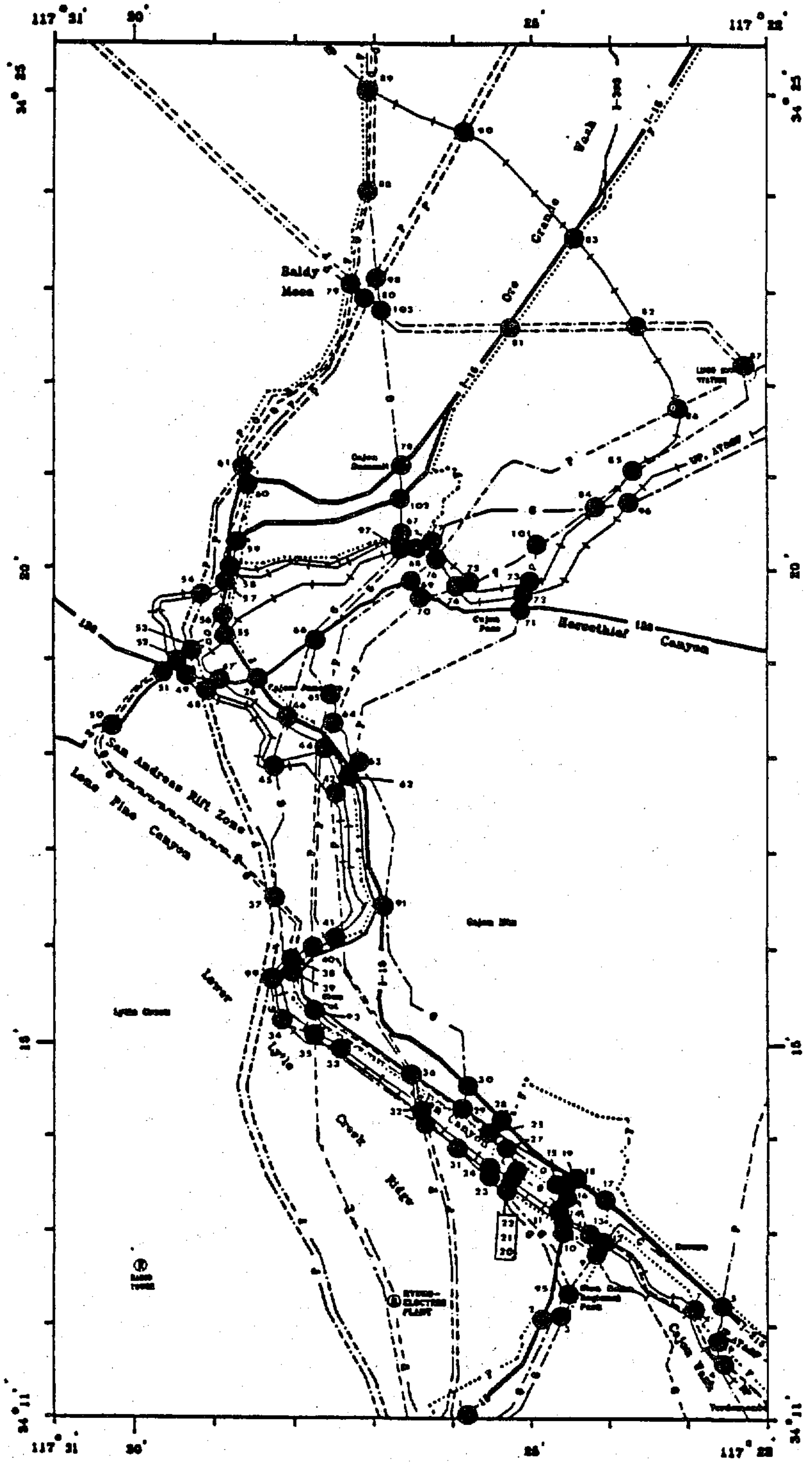
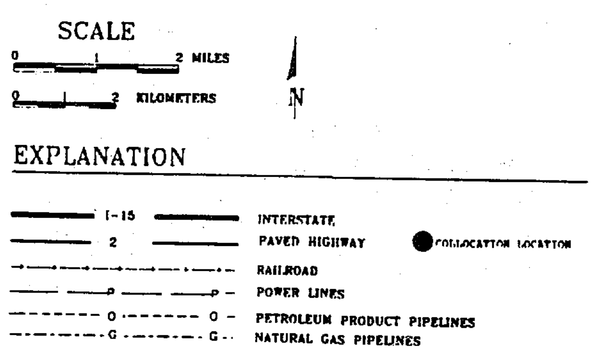


Figure 7, IDENTIFICATION OF LIFELINE COLLOCATION AT CAJON PASS



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The sensitivity study was performed with the QUAK2NW3 computer code[4,5] developed by the U.S. Geological Survey. Based on the study, the ground shaking intensities were relatively insensitive to the changes in fault rupture length The conclusions reached was that the 1857 Ft. Tejon earthquake was a reasonable choice for the study. It did not produce the most intense shaking, nor was it the least intensive. However, by using it for the present study, it will be possible to compare our solutions for earthquake intensity with those of previous researchers[5,6]. That comparison showed general agreement except at the fault rift zone. There the QUAK2NW3 program predicted lower shaking intensities than those reported by Davis[6]. After discussions with Davis, it was decided to increase the predicted MMI shaking intensity along the San Andreas fault zone by one level from VIII to IX. This accounts for the greater impacts that are expected to be associated with the fault displacement and is consistent with the work of Davis.

The areas of potential liquefaction were determined by examining the water well data for the Cajon Pass, and supplementing it with other regions high water table as determined by the site reconnaissance visits. Regions of high water table were correlated to alluvial deposits to identify the liquefaction susceptible regions. The historical landslides were identified[6,7,8] and the method of Legg (see Section 4.2, Table 7) was applied. A computer-based check of the soil conditions at the Cajon Pass was used to assure that the Legg method was applied at each slope of interest. The landslide predictions based on the Legg model agreed quite well with the record of historical landslides (that is, the Legg model prediction included the historical landslides, but it also identified many more potential areas of landslide).

Figure 8 presents the summary of the calculated seismic and geologic conditions overlaid upon the lifeline routes. Although the figure is complex and filled with data, it does highlight some important information. In the figure the shaking intensities are shown with various levels of shading. The highest intensities, MMI = IX, are along the San Andreas fault rift zone. On the map they are shown as solid lines where the fault is well located, dashed where its location is estimated, and circled when it is hidden by younger rocks. The potential landslides are predominantly south of the San Andreas fault and lie in a southeast trend. There are four important regions of potential liquefaction: just south of Cajon Junction, at Blue Cut where they coincide with potential landslide regions, southeast of Blue Cut about two miles northeast of the I-15/I-215 intersection, and just south of the I-15/I-215 intersection.

Figure 8 shows that many of the conditions of high MMI value, landslide, and liquefaction overlap. This is important to note because the lifeline components in the study area (with the exception of some bridges) are not very sensitive to shaking damage. MMI values of VIII generally would only cause damage state

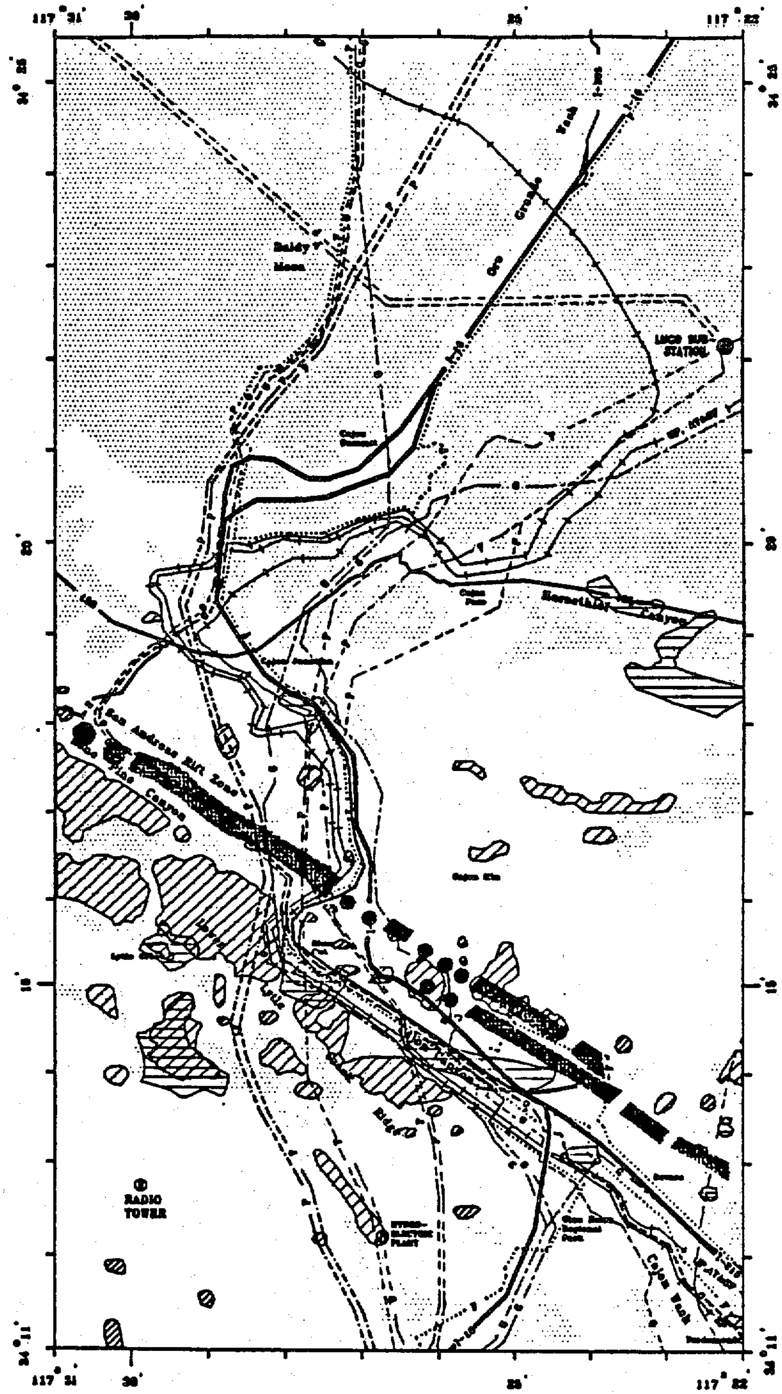
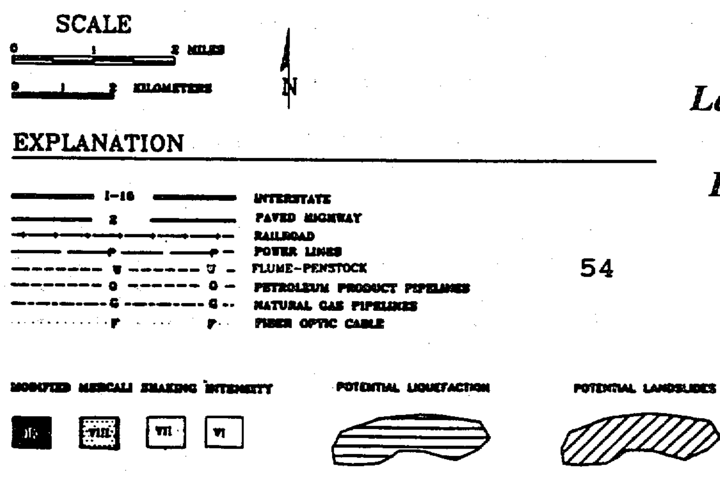


Figure 8, LIFELINE ROUTES WITH EARTHQUAKE SHAKING INTENSITY, AND POTENTIAL LANDSLIDE AND LIQUEFACTION AREAS



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2 or 3 to occur (less than 5% damage expected). At those conditions, collocation induced additional damage would be slight or none at all. However, the facilities are very sensitive to ground movement and there are a number of potential landslide or lateral spread (or liquefaction) locations along the lifeline routes that coincide with MMI = VIII. North of the San Andreas fault the earthquake risk comes predominantly from shaking, but most of the peak shaking intensities are VII with a few isolated locations of VIII.

Another important activity of the data acquisition phase of the study is to divide each lifeline into segments for subsequent analysis. Figures 6 and 7 were used to guide the segmentation process. The communication lifelines were divided into 12 to 14 segments, depending on the route of the individual fiber optic conduits; the electrical power transmission lifelines were divided into four segments (the Arrowhead Calelectric-Shannin line at the southeast corner of the study area was analyzed as a single segment); the natural gas pipeline lifelines were divided into five or eight segments; the petroleum products pipeline lifelines were divided into 10 segments; the railroad lifelines required 30 segments; and the interstate highway required 36 segments. The subsequent vulnerability calculations for the communication, electrical, and fuel pipeline lifelines were performed by hand; those for the transportation lifelines were performed with a standard computer spreadsheet. These approaches recognized the number of calculations that would be required.

5.2 Lifeline Collocation Vulnerability Analysis Results

Figure 7 identifies the locations of the 101 collocations that were subsequently analyzed in this study. These collocations involved over 250 separate potential lifeline interactions. Table 15 was prepared to identify the collocation and the lifelines that were involved at that location. As the collocation evaluation was prepared, the results were tabulated against the index, thus assuring that all potential interactions were located and evaluated.

Table 15 and Figure 7 identify several critical clusters of interactions. With this in mind, a collocation damage scenario was developed for each critical cluster of interaction. Using a standard collocation damage scenario at the critical clusters helped assure the overall consistency of the interaction analyses.

The clusters where the standard collocation damage scenario was used were:

1. The liquefaction zone south of the interchange of I-15 and I-215. There were 10 separate potential interactions involving I-15, railroad bridges, several fiber optic lines, the 16-inch natural gas pipeline, and the 8-inch and 14-inch

Table 15
MATRIX OF LIFELINE COLLOCATIONS AND INTERACTIONS

INTER-SECTION NO.	HIGH-WAYS					RAIL-ROADS			POWER LINES						FIBER OPTIC				NATURAL GAS			PETRO LINES	
	A	B	C	D	E	A	B	C	A	B	C	D	E	F	A	B	C	D	A	B	C	A	B
1	X									X		X											
2	X														X								
3															X				X	X			
4						X										X							X
5		X											X				X	X			X		
6							X						X								X		
7							X									X							
8	X																		X	X			
9															X						X	X	
10	X														X							X	
11						X	X								X							X	
12						X	X														X		X
13							X																X
14	X					X	X																
15															X								X
16																							X
17		X														X							
18		X														X							
19	X															X							
20																X				X			
21						X	X													X			
22																				X		X	
23						X									X								
24							X								X								
25			X												X	X	X	X		X		X	X
26	X			X																			
27																X						X	
28	X														X	X	X	X					
29			X												X	X	X	X		X		X	X

Table 15 (Continued)
MATRIX OF LIFELINE COLLOCATIONS AND INTERACTIONS

INTER-	HIGH-					RAIL-			POWER						FIBER				NATURAL			PETRO	
SECTION	WAYS					ROADS			LINES						OPTIC				GAS			LINES	
NO.	A	B	C	D	E	A	B	C	A	B	C	D	E	F	A	B	C	D	A	B	C	A	B
30	X																			X			
31						X													X				
32						X	X				X	X							X				
33						X													X				
34						X													X				
35						X	X			X													
36			X								X	X			X	X	X	X				X	X
37									X										X			X	X
38						X	X															X	X
39															X	X	X	X				X	X
40			X			X	X			X					X	X	X	X					
41			X			X	X				X	X			X	X	X	X					
42						X	X					X											
43						X				X	X												
44	X		X				X	X		X	X				X	X	X	X					
45						X		X											X				
46							X								X	X	X	X	X				
47				X			X																
48				X		X		X	X														
49				X		X		X															
50					X																		
51				X	X																	X	X
52						X		X														X	X
53									X													X	X
54						X		X	X														
55	X						X								X	X	X	X					
56	X														X	X	X	X				X	X
57	X					X		X															
58						X		X							X	X	X	X				X	X

Table 15 (Continued)
MATRIX OF LIFELINE COLLOCATIONS AND INTERACTIONS

INTER-	HIGH-					RAIL-			POWER						FIBER				NATURAL			PETRO	
SECTION	WAYS					ROADS			LINES						OPTIC				GAS			LINES	
NO.	A	B	C	D	E	A	B	C	A	B	C	D	E	F	A	B	C	D	A	B	C	A	B
59	X														X	X						X	X
60	X														X	X						X	X
61									X						X	X						X	X
62	X		X									X			X	X	X	X					
63												X									X		
64											X										X		
65										X											X		
66				X																X	X		
67						X	X	X												X	X		
68							X	X													X		
69				X						X													
70				X							X												
71				X								X											
72							X					X											
73						X						X											
74							X				X												
75						X					X												
76						X	X	X		X													
77						X														X			
78	X																		X				
79														X	X	X						X	X
80									X					X					X				
81	X													X			X	X					
82						X								X									
83	X					X											X	X					
84						X					X	X								X			
85						X					X	X											
86						X				X													
87									X	X	X				X								

Table 15 (Continued)
MATRIX OF LIFELINE COLLOCATIONS AND INTERACTIONS

INTER-	HIGH-					RAIL-			POWER						FIBER				NATURAL			PETRO	
SECTION	WAYS					ROADS			LINES						OPTIC				GAS			LINES	
NO.	A	B	C	D	E	A	B	C	A	B	C	D	E	F	A	B	C	D	A	B	C	A	B
88															X	X				X		X	X
89						X									X	X				X		X	X
90						X			X														
91	X																			X			
NOT USED																							
93			X																				
NOT USED																							
95															X				X	X	X		
96							X													X			
97							X												X	X			
98									X										X				
99									X										X				
100										X										X			
101										X	X												
102	X																		X				
103														X					X				

petroleum products pipelines. All of the buried lifelines were found to have incurred damage state 7 (catastrophic) with probabilities that the damage occurred of 40%. The assumed collocation interaction was that the petroleum pipelines could drain 1-2 miles of pipe but that no secondary fires or explosions would occur. This contributed to an additional 30 day delay to the site before repair could commence, due to the requirements to assure that fire conditions and environmental concerns could be alleviated before work could start on the individual lifelines. An additional 10 days of delay were hypothesized due to the need to coordinate the work on so many individual lifelines.

2. A second cluster exists along the Cajon Blvd. extension into the Cajon Pass from north of the I-15/I-215 interchange to Blue Cut. There are two separate locations where

landslides (with a probability of occurrence of 45%) and two liquefaction areas (probability of occurrence of 20% and 40%) are possible, including eight separate collocation impact areas where there are collocated power lines, railroads, and a natural gas pipeline. At the two landslide areas along the Cajon Blvd. extension (which was the prior highway 66 before I-15 was built), a natural gas pipeline and the railroads are located at the toe of the slide area, and landslide debris is expected there. Debris removal for clearing the railroad would be required before work on the pipeline (which is located in the railroad right-of-way and sometimes under the rail bed) could begin. The debris removal was assumed to cause a 30 day delay before work on repair of the pipeline could occur.

3. At Blue Cut itself there is another landslide and liquefaction zone. Due to its proximity to the San Andreas fault rift zone, a 70% probability of occurrence was estimated. At that location, a power line, a natural gas pipeline, and a railroad are in the flow area of the slide, which could cause the pipeline to surface and rupture as well as to be covered with debris. The collocation damage scenario assumed that an explosion and fire could result, increasing the damage to the power line and its repair time by an additional 20 days, compared to the delays described for the other slide area, to repair the more extensive damage the fire caused. The potential for landslides blocking the Cajon Creek with a slide dam, and the subsequent impact on downstream lifelines if the dam should catastrophically fail were considered to be outside the scope of this study. At Blue Cut itself, the liquefaction zone has a 50% probability of occurrence.

4. In the San Andreas fault rift zone there are six collocation points that involve the power lines, the railroads, the fiber optics, a natural gas pipeline, the two petroleum products pipelines, and the Cajon Blvd. extension. Fuel spills are assumed to require a 30 day delay for alleviating environmental and fire concerns. An additional 60 day delay was assumed for the petroleum products pipelines because the estimated extensive damage to their right-of-way along the fault trace will require regulatory review and acceptance before the pipeline can be worked on. An additional 30 day delay for the other lifelines was assumed because of the general congestion in the area. Since the fault displacement causes catastrophic failure of the lifelines, the collocation damage scenario does not assume any further damage.

With these scenarios in mind, the collocation vulnerability analysis was performed for each separate lifeline system.

Communication Lifelines

Figure 9 shows the communication lifeline routes in the study area. The location of the photographs presented in this section of the report are also shown on the figure. The microwave, radio, and cellular phone communication towers are sited such that they are not collocated with other lifelines. Thus, they do not enter into the analysis of the impact of collocation. The impact of degraded communications (if these towers should fail) on the ability to restore the other lifeline systems to acceptable delivery conditions is beyond the scope of the present study.

There are five fiber optic systems located in the study area. They include American Telephone and Telegraph (AT&T), Continental Telephone (Contel), MCI Communications (MCI), WTG West (WTG, formerly WilTel), and US Sprint.

The individual fiber optic cables are multi-layered with an inner structure that allows the cable to be pulled and maintained in a state of tension without placing tension on the individual glass fibers. This assembly is then wrapped with various insulating materials, including a metal sheath. In the fall of 1986, the U.S. Forest Service provided MCI and WTG right-of-ways on the basis that they would each provide two conduits and that each conduit would be four inches in diameter so that cables from two different systems could be placed in each individual conduit (thus, provisions were made to lay eight cable systems along the two routes through the Forest Service land). Furthermore,the Forest Service required that the routes be combined as quickly as practical. Thus, the MCI and Contel systems enter the study area from the north along Baldy Mesa Road, while the AT&T, WTG, and US Sprint systems enter from the north along the access road to I-15. The routes join together just south of the separation of I-15N and I-15S (about 1.8 miles north of the Cajon Junction of I-15 and Highway 138). From there they travel together as a bundle of four conduits. Much of their route is along the Cajon Blvd. extension where they are laid in the median strip. Also routed along much of the median strip are the two petroleum products pipelines (the Cajon Blvd. extension was the former divided highway 66, but only the western two lanes are still maintained for traffic). For the purposes of this study, the fiber optic cables are analyzed as buried conduits. Because of their collocation, if one conduit fails, all fail.

When the conduits (which are normally buried) are routed to a bridge location, they are generally brought to the surface and hung with light anchors from the bridge. Figure 10 shows them on a typical bridge crossing on the abandoned portion of Highway 66; Figure 11 shows some of the details of the bridge hangers and the conditions of the conduits; Figure 12 shows them hung from a highway culvert wall just south of Cajon Junction; Figure 13 shows some of the details of the wall anchors near the culvert location of Figure 12. Just south of the culvert shown in Figure 12 the

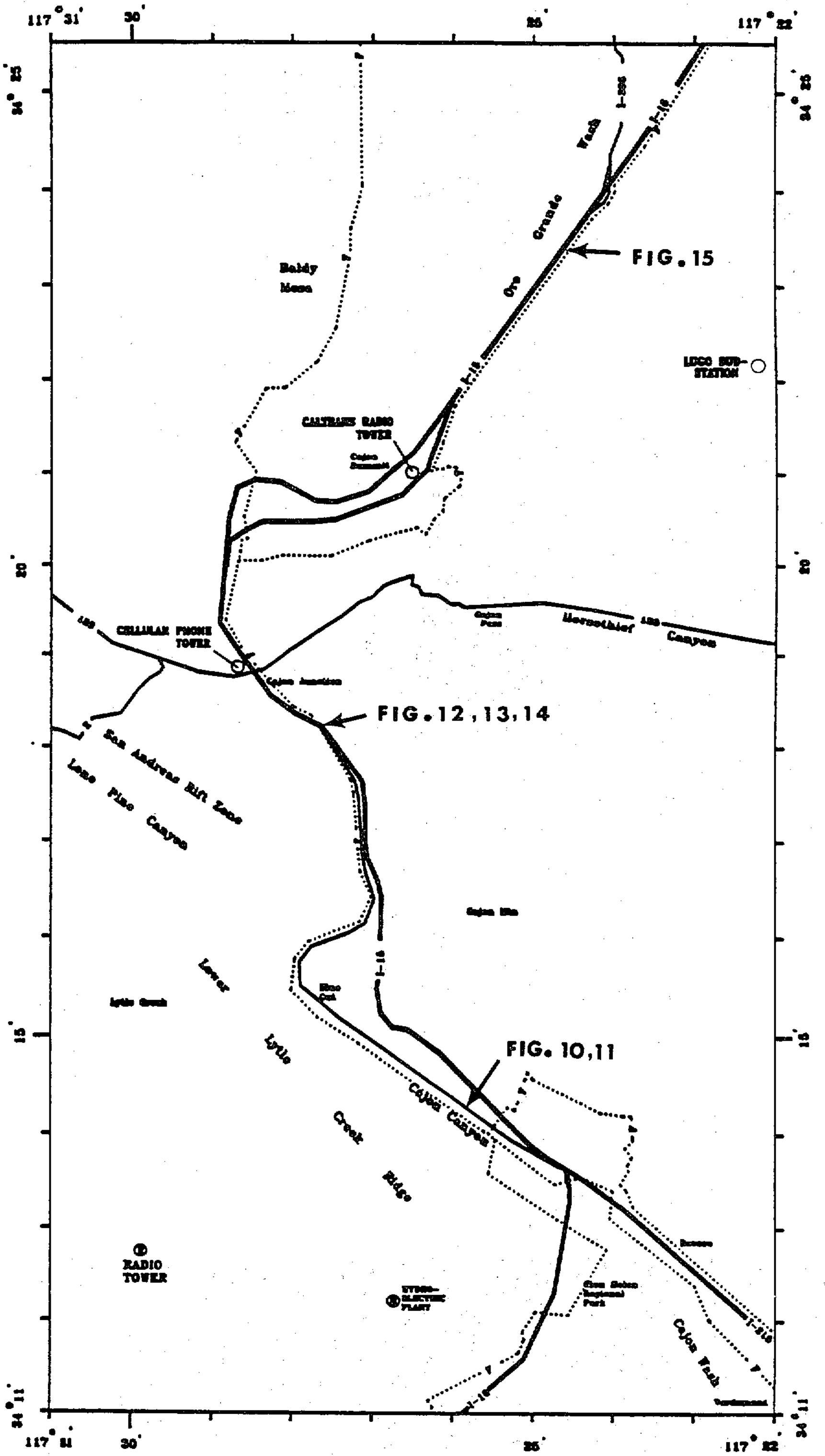


Figure 9 COMMUNICATION LIFELINE ROUTES

SCALE

0 1 2 MILES

0 1 2 KILOMETERS

N

EXPLANATION

I-15 INTERSTATE

2 PAVED HIGHWAY

F F FIBER OPTIC CABLE

Larger Scale Figure Located at End of Document

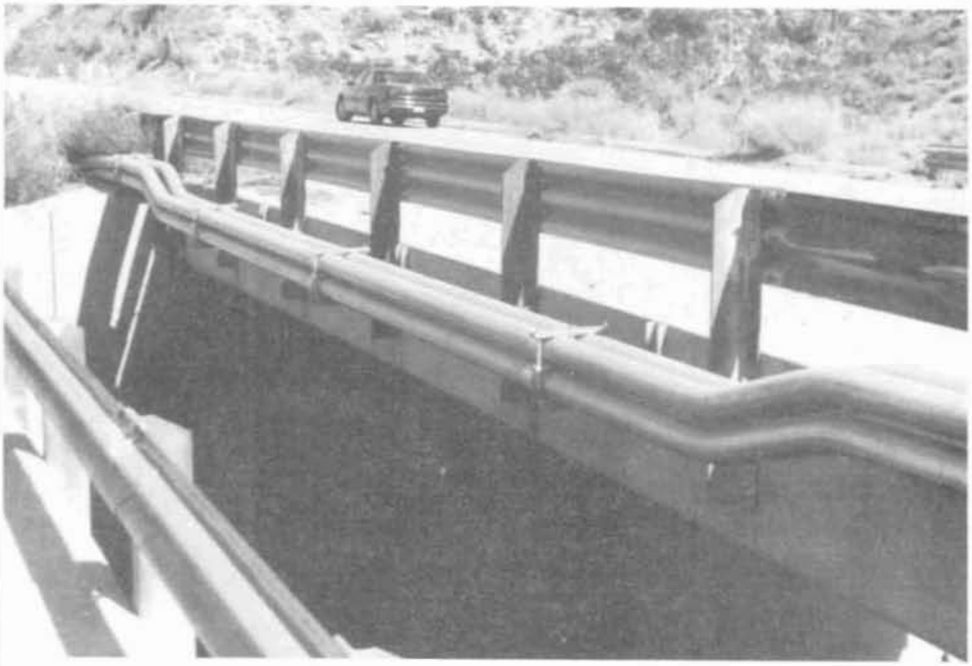


Figure 10 Fiber Optic Conduits On A Bridge On The Abandoned Portion of Cajon Blvd. Extension

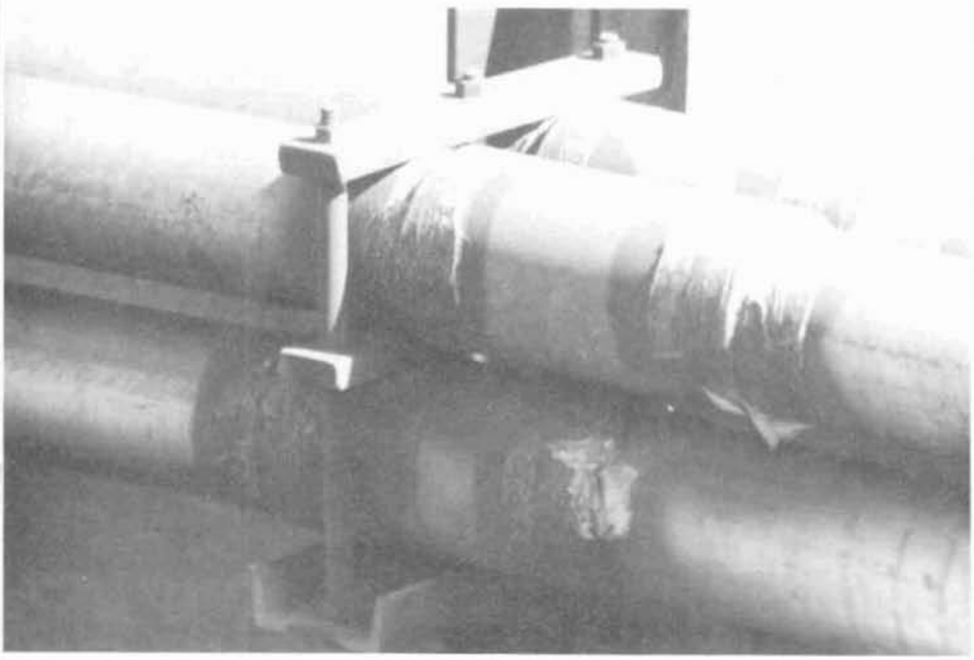


Figure 11 Details Of The Fiber Optic Conduits Of Figure 10

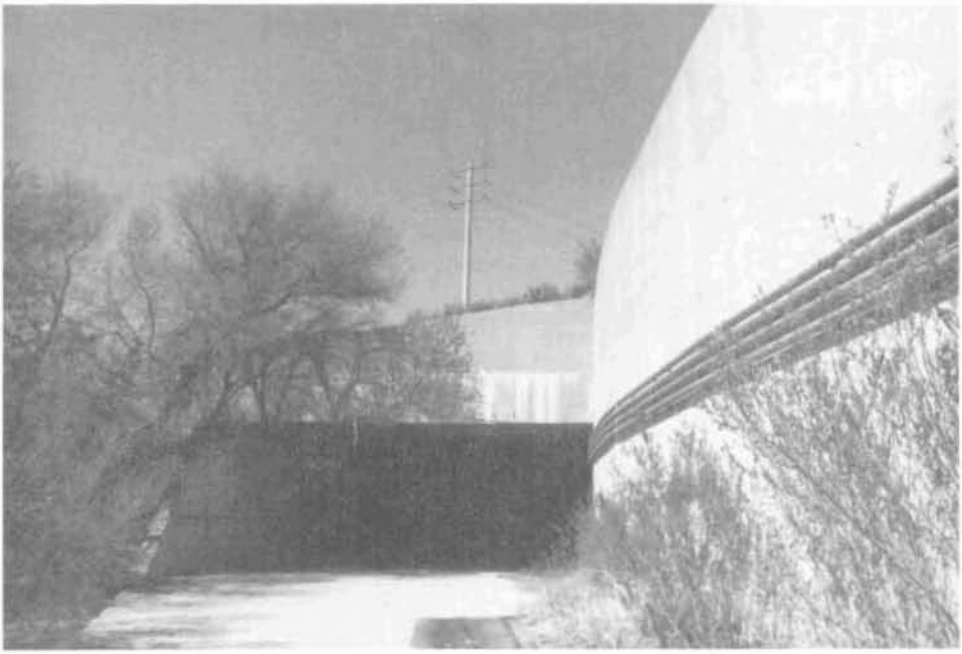


Figure 12 Fiber Optic Conduits On A Concrete Culvert That Passes Under I-15

Figure 13 Wall Support Details For The Fiber Optic Conduits Of Figure 12

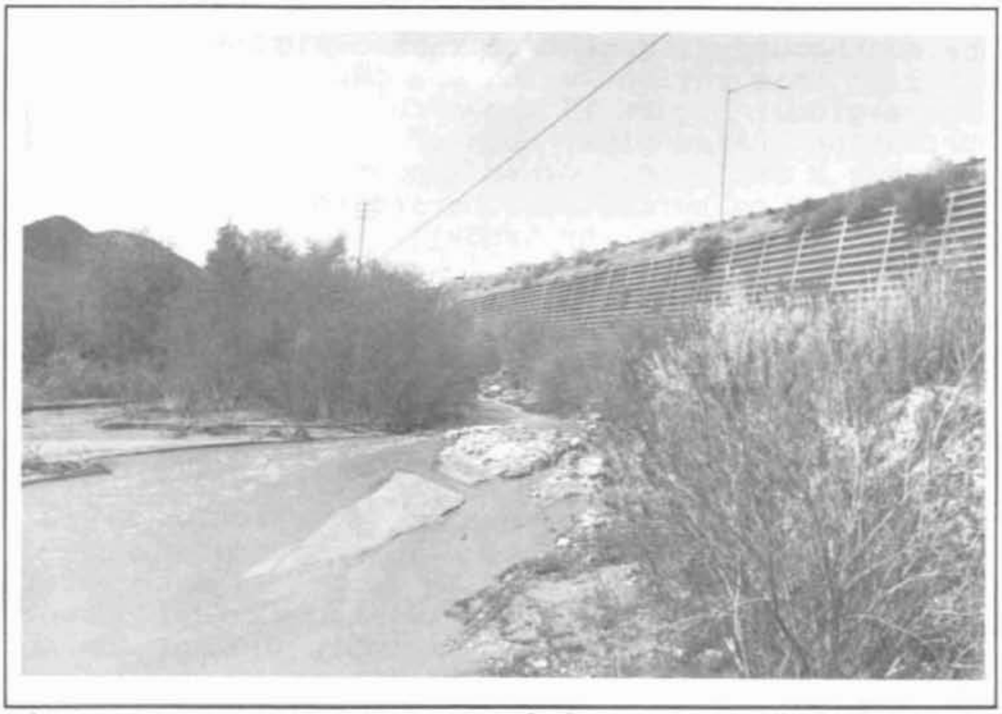


Figure 14 Surface Water Conditions Near The Toe Of The I-15S Retaining Crib Wall

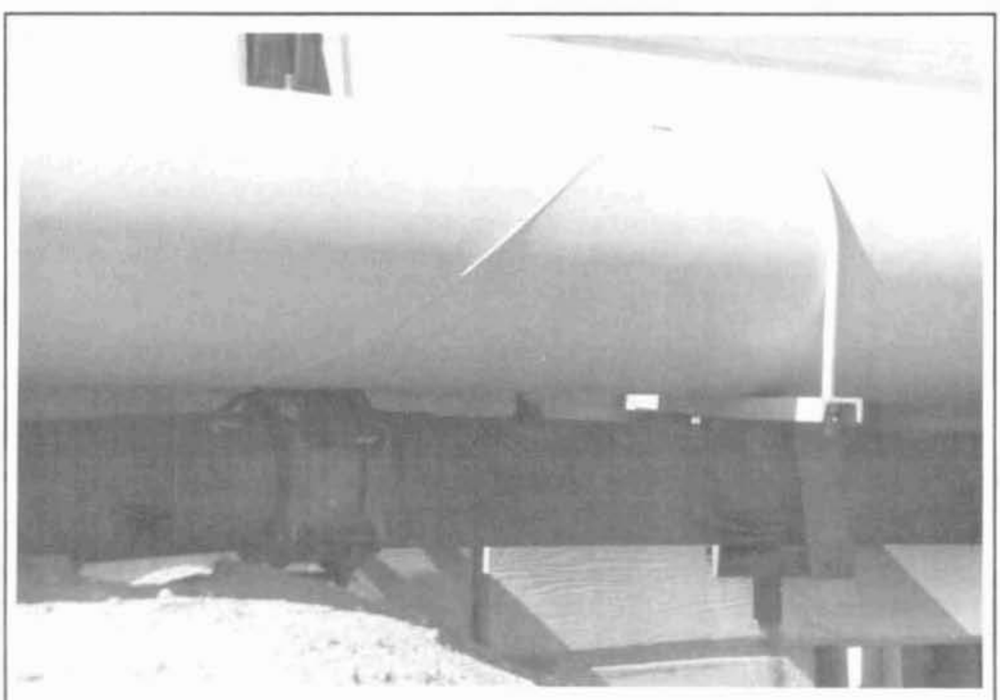


Figure 15 Fiber Optic Conduits Under a Heavy Water Pipe, Both On A Highway Bridge

fiber optic cables are buried at the toe of a crib wall used to support the southbound alignment of I-15. Figure 14 shows the surface water in this region, which was identified as a potential liquefaction region. Figure 15 shows the conduits hung under a water distribution system pipe, both of which are supported from a road bridge over a railroad. Other important collocations include where the conduits are buried near buried fuel pipelines, a number of which are in liquefaction or landslide prone regions.

In all of these cases, the fiber optic cables are at potential risk because the light anchors used could be expected to fail due to shaking. The heavy water pipe just above the fiber optic cable conduit can be expected to fall on and fail those cables.

The analysis of the fiber optic cable systems indicates that they are not at significant risk until the MMI values equal VIII or more. In the Cajon Pass that occurs at liquefaction areas or at the San Andreas fault where surface displacements of up to 12 meters are anticipated. Thus, shaking damage is not expected to be significant compared to displacement-related damage. However, the screening method data base does not directly account for the light anchors and the conditions of the conduits as shown in the figures. It is possible that they are more sensitive to shaking damage than the screening method predicts.

At the San Andreas fault location (just north of and close to Blue Cut) the fiber optic conduits are not collocated with other lifelines within the zone of influence of the lifeline. Thus, for purposes of this study there is no collocation impact there. However, the large number of near by lifelines does suggest that general construction congestion could delay the permanent repair of the communication lifelines in this region. Also, it probably would be possible to temporarily lay the fiber conduits on the ground surface, restoring service on a temporary basis. These types of changes to the assumed restoration of service time are noted, but they were not used in the present study to estimate the service restoration time.

Four liquefaction regions have the potential to impact the fiber optic systems. At the liquefaction region just southeast of the I-15/I-215 interchange, the fiber optic cables are in separate and dispersed conduits. However, two cable conduits cross this zone near the railroad beds. One cable conduit crosses the 16-inch natural gas pipeline and the 8-inch petroleum products pipeline, and then it runs parallel to the 8-inch line. Another cable conduit crosses the liquefaction zone and is perpendicular to the 16-inch natural gas pipeline, which is also in the liquefaction zone. The liquefaction impact is calculated as a damage state 7 (catastrophic) but it only has a 40% probability of occurring. The conduit repair time in this region is hypothesized to triple, based on the delays required to repair the natural gas and the petroleum products pipelines and the delays associated with the repair of the nearby damaged I-15 and railroad bridges. This causes the fiber optic conduits' most probable repair time to increase by about ten days.

In the second liquefaction region the four cable conduits are collocated and they are parallel and next to the 8-inch and 14-inch petroleum products pipelines. In this region they cross over the 36-inch natural gas pipeline. The liquefaction impact is a damage state 7 with a 20% probability of occurrence. The collocation damage scenario assumed that the petroleum product pipelines would have to be repaired before the fiber optic cables could be replaced within their conduits along their old route, causing a 55 day delay in being able to access the five fiber optic cables. Another 10 days delay for equipment availability is expected. However, the low probability of liquefaction resulted in the most probable restoration time increasing by only about four days.

The third liquefaction zone is just south of Blue Cut. The collocated lifelines include the fiber optic conduits, fuel pipelines and a high voltage power line also crosses over the region. The liquefaction probability at this locations is estimated at 50%. Most of the repair activities for the power line will not impact the fiber optic cable conduit repair. The only impact could come when the power lines directly over the conduits are being worked on. The most probable restoration time increased by only about 12 days.

The fourth liquefaction zone is where the fiber optic conduits cross the toe of an I-15 retaining wall crib and then are connected along the concrete culvert under I-15 (see Figures 13 and 14). The concrete culvert is a massive structure, and its damage is expected to be small. Analysis of the crib wall found that its movement would not substantially impact the highway, however, just partial movement of the crib wall could severely damage the fiber optic cables. In such a case they could not be replaced permanently until the wall had been stabilized. Fortunately, the probability of liquefaction is only 40% in this region, resulting in the 140 day crib wall-induced delay becoming a 22 day most probable restoration time increase for the fiber optic conduits.

Where the AT&T and WTG cables are hung from the bridge over the Southern Pacific railroad is the final collocation damage location where the collocation impacts were found to be serious (see Figure 15). There, because the shaking intensity is only MMI=VII, not much damage would normally be expected to the cable conduit itself. However, the wall brace and anchor supports for the water pipe and the fiber optic conduit are small and have not been sized for earthquake conditions. Thus, it was assumed that they fail allowing the fiber optic conduit to sag. The heavier water pipe was assumed to fall on top of the fiber optic conduit which is located directly under it, causing the fiber optic conduit to rupture and fail. The probability of this failure scenario is estimated to be 80%, causing the most probable restoration time to increase by about 4 days.

Thus, of the 55 collocations analyzed for the fiber optic systems, nine were estimated to lead to increased probable times to restore service. Most of these conditions resulted from ground motion-induced failures, and the impact on the fiber optic systems was that the failures of the other collocated lifelines lead to increases in the delay time before the fiber optic systems could be repaired. The practice of collocating all of the fiber optic conduits together, along with the practice of hanging them from bridges and culverts with very light anchor bolts, suggests that in future earthquake situations the loss of telephone communications will be more severe than have been experienced in the past. That is because the loss of a few hard-wired telephone lines in past earthquakes has not been significant in terms of the ability of the systems to handle call traffic. Fiber optic cables, however, handle many more calls per line than does a hard-wired system, and if one cable is lost then probably all of the collocated cables will be lost in the same event.

The overall estimate of the impact of collocation on the communication lifelines was:

Lifeline	Increase in Probable Time to Restore Service, days	Increase in Probable Time to Restore Service, %
Fiber Optic Cables	61	86

Electric Power Lifelines

Figure 16 shows the electric power transmission lifeline routes in the study area. The location of the photographs presented in this section of the report are also shown on the figure. Experience has shown that power transmission towers are quite resistant to earthquake shaking, principally because of the conservative wind loading criteria used in their design. Thus, only fault displacement, landslide, or liquefaction are expected to caused significant levels of damage to the towers.

The electric power lifeline systems include a major transmission system substation at Lugo in the northeast corner of the study area, a hydroelectric generation station in Lytle Creek Canyon, and four major high voltage transmission systems. The hydroelectric station is not collocated with any of the lifeline components of interest to this study. Although the substation is collocated with two of the high voltage transmission systems, component failures in the substation are not expected to lead to transmission line failures, and visa versa. The transmission lines are not expected to have any failures at the shaking intensity expected at Lugo

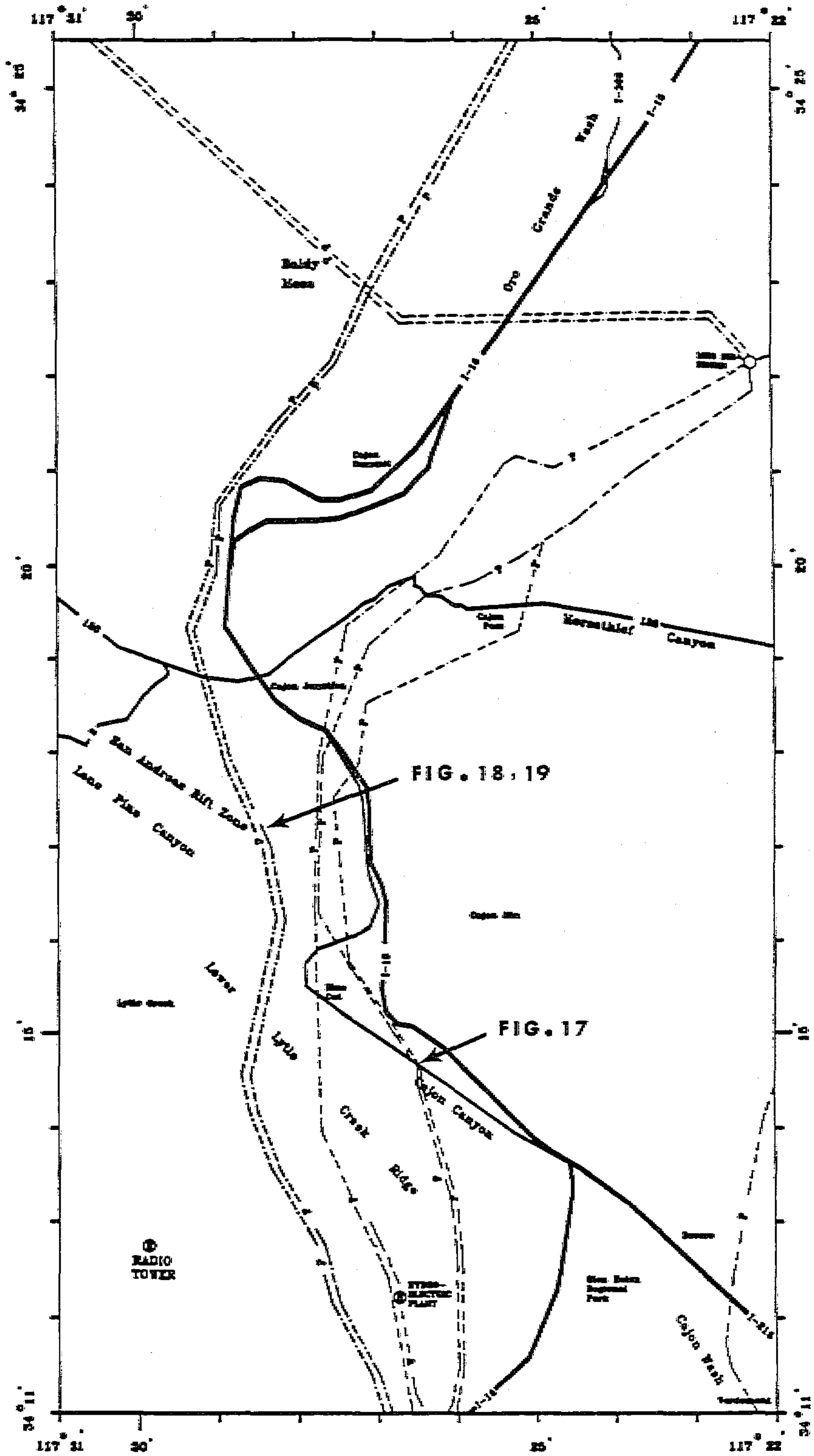
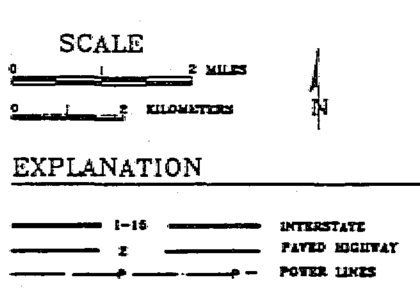


Figure 16, ELECTRIC POWER LIFELINE ROUTES



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(where MMI = VII). Thus, although the substation is a potential weak link in the overall electric power transmission system, the lack of collocation impacts means it was not be examined further in the present study.

In general, power transmission lines are not impacted directly by the other lifelines, as they are either above or otherwise outside of the zone of influence of the other lifelines. However, they can be impacted by construction delays or fires induced by the failure of other lifelines. The general tower design and footings used are quite rugged and earthquake resistant (resistant to shaking damage). There have been some cases when shaking has caused the lines themselves to gallop or vibrate, resulting in their coming close or even touching other lines routed on the same tower. The resulting arc and electrical short can cause fires and/or drop both lines from service. However, this failure mode is not addressed in the available data base and thus was not considered in the present study.

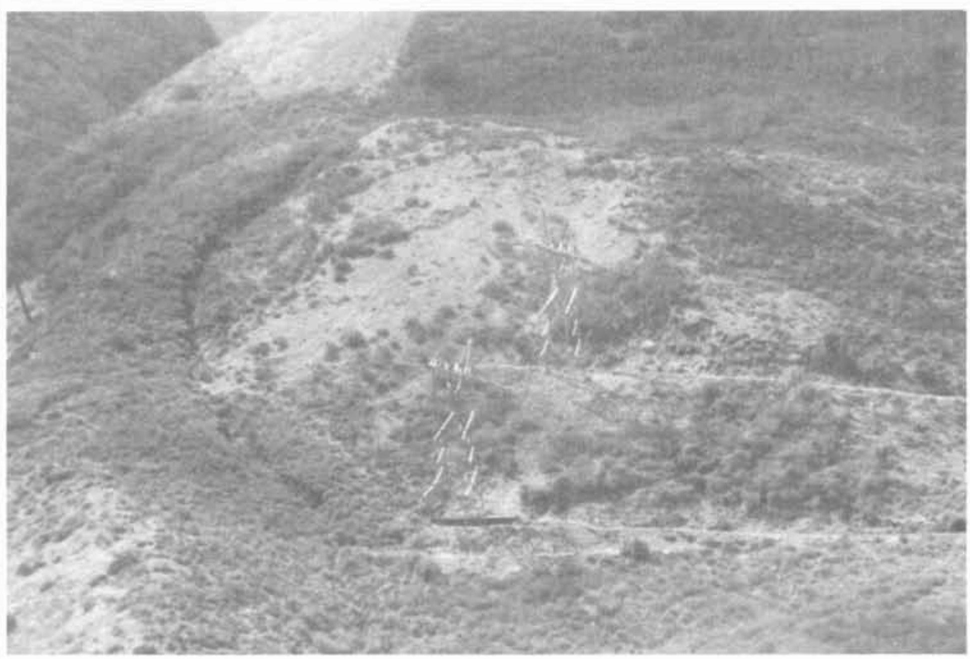

Figure 17 A Landslide Scar With Power Towers In The Slide Area

Transmission lines often traverse more rugged areas, and as such they are susceptible to landslide damage. Figure 17 shows two transmission towers located in an old landslide scar (the original towers were damaged in the landslide). This location is an important collocation site, as a buried natural gas transmission pipeline and the railroad tracts are located just below the slide area. Figure 18 shows the location of two high voltage power transmission tower systems, a buried natural gas transmission pipeline (shown by a surface marker), and the 8- and 14-inch buried petroleum products pipelines (also shown by a surface marker).

This location is in the fault rift zone of the San Andreas fault (in Lone Pine Canyon). Figure 19 is a photograph from the same location looking in the opposite direction. It shows a transmission tower located at the edge of a steep ravine where it is subject to possible landslide failure. This general location (in the San Andreas fault and rift zone) is the most significant collocation condition for the electric and the fuel lifelines.

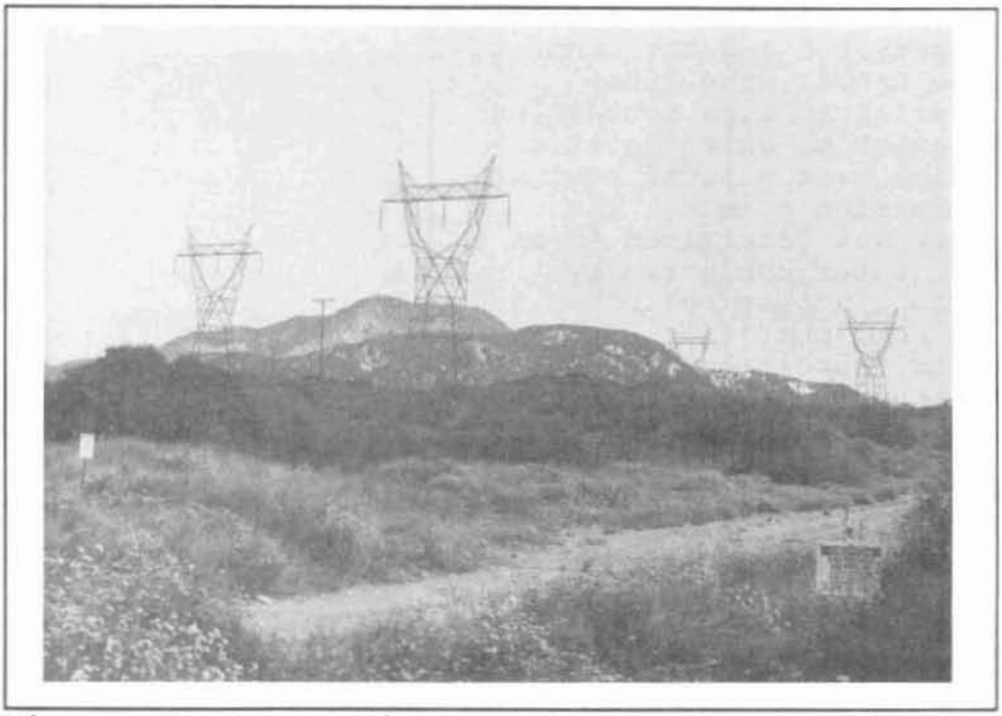

Figure 18 Power Lines, Natural Gas & Petroleum Products Pipelines Intersection Over the San Andreas Fault Rift Zone

The Southern California Edison (SCE) 115 kV Arrowhead:Calelectric Shannin transmission line (located in the southeast corner of the study area) is routed through some local landslide and liquefaction zones, however, it is not collocated at those regions. Its other collocation impacts were negligible. In the northern section of the study area the SCE Lugo-Vincent two-line, 500 kV transmission lines traverse from Lugo station west and then northwest. Because of the low shaking intensity (low for power lines), they only experience damage state 1 or 2. Thus, these two SCE transmission systems are not of interest for collocation impacts in the present study. There are, however, a Los Angeles Department of Water and Power (LADWP) two-line transmission system and a three-line SCE transmission line system that resulted in collocation impacts.

The LADWP Victorville:Century 287.5 kV transmission line system (it has two full circuits) extends from the north (located at about the center of the northern boundary of the study area) to the south of the study region. It was constructed in 1936 to transmit power from the Hoover Dam in Nevada to the Los Angles Basin. It has been upgraded in 1970, 1974 and 1980 to allow switching between the 287.5 and other 500 kV lines as well as to add new controls. Parts of the line have previously experience problems of interest to this study. At a section between Highway 138 and the Lone Pine Canyon, the lines experienced slow foundation movement or shifting at a region were a local bowl or depression exists. The cause was determined to be a high water table fed by surface waters collected in the bowl that allowed the tower foundations to slowly respond to the tension imposed by the lines themselves. The solution was found to be to cover the ground with a concrete mixture so that surface waters would could not seep into the water table at that location. The towers now appear to be stable. On several other occasions, local brush/forest fires have heated the copper conductors to the extent that they partially annealed and sagged. This problem was resolved by retensioning the line in those regions. It is of importance because it indicates the problems that earthquake-induced fires could have on this lifeline system.

Figure 19 Power Tower At A Ravine Edge In The San Andreas Fault Rift Zone

The LADWP power lines cross the San Andreas fault zone in Lone Pine Canyon very close to where the petroleum products and a 36-inch natural gas transmission line cross the fault trace (see Figures 18 and 19). The expected 12 meter fault displacement causes a damage state 7 to all the lifeline components in this region, with a probability of 100%. The collocation scenario assumes that the resulting petroleum products spill (several miles of those pipelines could drain from the rupture, depending on how many other ruptures are assumed since the petroleum products pipelines run parallel to the fault trace for several miles) causes a 30-day delay in the repair activities while the resulting environmental and fire hazards are evaluated and mitigated. The general congestion in the area and the need to coordinate the use of heavy equipment so that its use will not adversely impact the other lifelines is assumed to add another seven days to the power line repair times. Because of the high probability of damage at this location, the probable restoration time increases by 37 days. This accounts for about 75% of the collocation-induced delays in the restoration of service to the LADWP power lines.

The other significant collocation region for the LADWP power lines is also at Blue Cut. The power lines cross the eastern edge of a landslide zone, and at the toe of the zone at a lower elevation a 36-inch natural gas pipeline is sited next to and in the right-of-way of a rail line. The probability of a slide in this region is 70%, it produces a power line damage state of 5 (heavy damage). The collocation scenario includes a seven day period while the gas line is prepared and tested for leaks, and a increase in damage state to level 6 because of potential natural gas pipeline failure impacts. That scenario increased the repair time from 49 to 66 days and the net impact on the change in restoration time was about 12 days.

There are three 500 kV circuits on SCE's Lugo - Mira Loma system. They were installed in the early 1960s for about 300 kV service and upgraded to 500 kV service in the early 1970s. Line 3 was added in 1983.

Line 1 is to the west, line 2 is in the center, and line 3 is the eastern line. Line 1 is routed south by southwest from the Lugo substation. Lines 2 & 3 leave Lugo station on a single tower system for about 1.5 miles, then they divide into two separate tower systems. The power lines cross the railroad lines a short distance before they cross Highway 138. From there they head generally south until they cross I-15. In this high desert region the only earthquake load comes from shaking characterized by MMI = VII. At that intensity there is no appreciable damage to the towers or the lines, and no collocation impacts were hypothesized.

At the I-15 crossing, lines 1 & 2 cross at the northern boundary of a local liquefaction zone. Because their power towers are located on local hill tops in this region, it is assumed that there are no impacts due to the liquefaction or due to collocation. However, they cross near a concrete culvert that crosses under the highway. At the culvert (see Figure 12) location there is also a metal crib wall (see Figure 13) that provides support to the road bed, the fiber optic cables cross at the same location, there are two railroad bridges in the downstream path from the run off that passes through the culvert, and there is a 36-inch natural gas line which crosses I-15 in the same area. In addition, the crossing is in an area of high water table and of surface water, indicating a potential liquefaction zone. Although the power towers and lines are not expected to experience damage at this location, they will cause some delays in responding to damage on the other lifelines because of the need to work with large cranes and other equipment that could get close enough to the power lines to cause the need for caution to avoid potentials for electrocutions, etc.. Line 3 crosses I-15 further south and is not impacted by the crowded conditions described above.

After crossing I-15, lines 1 & 2 are routed as parallel lines. Where they cross the San Andreas fault they will experience damage state 7 due to the 12 meter displacement expected at the fault trace. The two lines pose a collocation potential that is assumed to increase their repair time by 15 days. This increases their probable restoration time by 15 days because of the high probability that the large fault displacement will occur. After this, the lines again separate, with line 1 heading south, and line 2 heading southeast until it joins with line 3 at Blue Cut.

As line 1 heads south it enters a liquefaction zone that is north and abuts against a landslide zone. Within the liquefaction zone it crosses over the two petroleum product pipelines, the fiber optic conduits, and Cajon Blvd. extension. Near the boundary between the liquefaction and landslide zones it crosses over a 36-inch natural gas pipeline that is itself next to and in the right-of-way of a railroad line. The liquefaction zone results in a 50% probability of damage state 7 occurring to the power towers. The collocation scenario is a 20 day delay due to the general congestion in the region, which results in a probable delay in restoration of 4 days. There are no other significant collocation regions for line 1 further south along its route.

After they join together, lines 2 & 3 head in a south by southeast direction. They cross the Cajon Blvd. extension at the northern boundary of a local liquefaction zone and head up the steep slopes to the higher elevations of the San Gabriel Mountains. Just above the Cajon Pass floor as they rise into the mountains they enter a landslide zone. Figure 17 shows that in the past they have experienced slides that have required extensive repair. At the toe of the slide a 36-inch natural gas pipeline is located next to and in the right-of-way of a railroad bed. The landslide causes a damage state 5 (with a probability of 45%). It is assumed that the congestion and the need to shut down the power line when the gas pipeline is to be tested for leaks will add 40 days to the repair of the power towers. This makes their probable restoration time increase by nine days at this location.

The typical collocation damage scenario is that other lifelines have a minor physical impact on power lines because the power lines are above or removed from the zone of influence of the other lifelines. However, when fuel-based lifelines are involved, they can cause important delays in the power line restoration. This is to assure that the power lines do not become a source of ignition for the fuel. Also, when the other lifelines are directly under the power lines, the expected use of temporary support towers may not be acceptable because of the increased risk of electrocution when other large repair equipment is operated near a temporary tower. As was the case for the communication lifelines, ground movement was the principal cause of electrical transmission lifeline damage.

One hundred and four collocations involving the electric power lifelines were analyzed. The overall estimate of the impact of collocation on the electric power lifelines in the Cajon Pass was:

Lifeline	Increase in Probable Time to Restore Service, days	Increase in Probable Time to Restore Service, %
Los Angeles Dept. of Water & Power	49	28
Southern California Edison Co. Line #1	19	10
Southern California Edison Co. Line #2&3	28	13

Fuel Pipeline Lifelines

Figure 20 shows the fuel pipeline lifeline routes in the study area. The location of the photographs presented in this section of the report are also shown on the figure. The lifelines include one 8- and one 16-inch petroleum products pipelines, three 36- and one 16-inch natural gas pipelines, and the associated valves for each line. Modern buried pipelines of the type installed at Cajon Pass are very resistant to shaking damage. Thus, the earthquake conditions of most interest for the pipelines are the conditions where ground movement is expected. However, when they are buried next to or under another

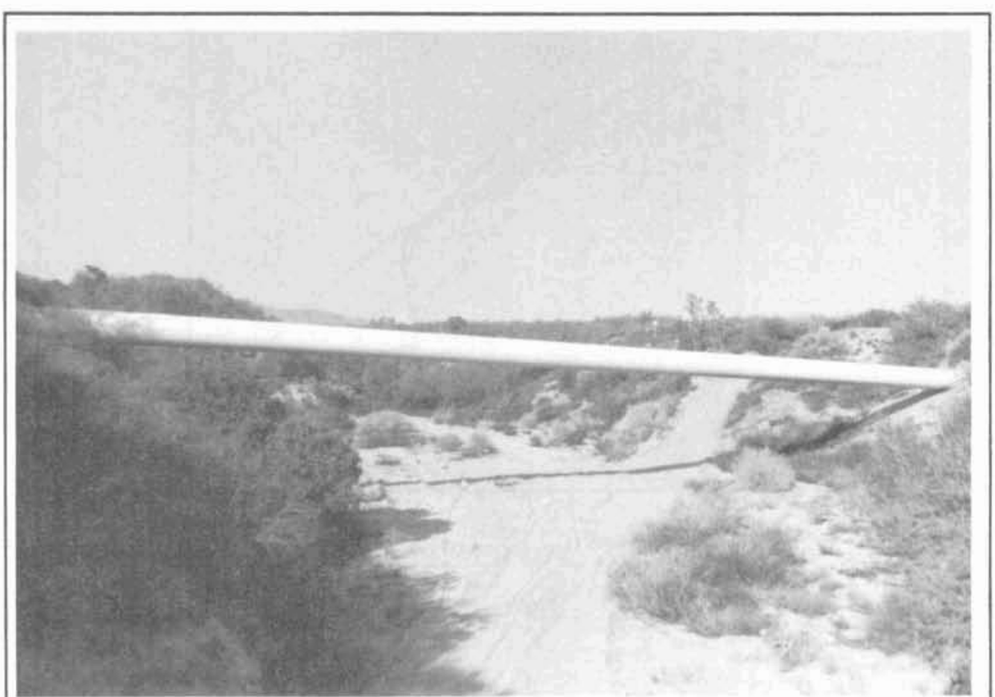

Figure 21 Typical Long Open Span On The 36-Inch Natural Gas Pipeline

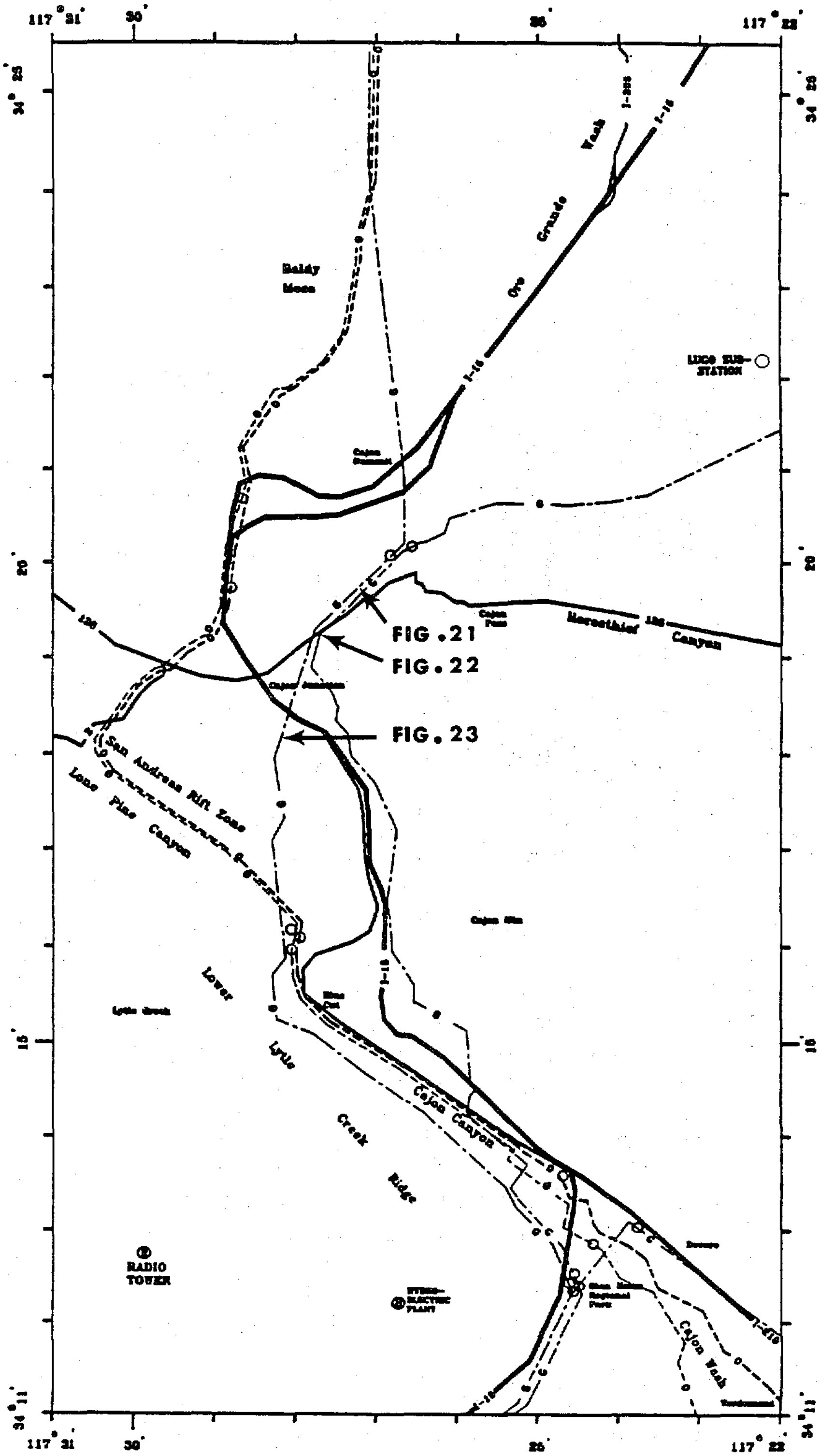

Figure 20, FUEL PIPELINE LIFELINE ROUTES

SCALE

0 1 2 MILES

0 1 2 KILOMETERS

N

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EXPLANATION

I-15	INTERSTATE
2	PAVED HIGHWAY
O	PETROLEUM PRODUCT PIPELINES
G	NATURAL GAS PIPELINES
○ ○ ○	VALVES

lifeline (as they are with the railroads), there is an additional concern that heavy equipment used to remove debris or otherwise restore the railroad lifeline could lead to pipe wall damage of the nearby buried fuel pipeline.

Figure 22 Two Natural Gas Pipelines Near Highway 138, One Buried, One Exposed

Because they are buried, there are no convenient features that can be shown with photographs. However, there are 18 locations along the route of the western most 36-inch natural gas pipeline that are exposed spans which range from 10 to 138 feet in length. Figure 21 shows one of the longer spans across a dry creek bed north of Highway 138 and east of I-15. Figure 22 shows a location about 40 feet from the recently realigned Highway 138. At that location two 36-inch natural gas pipelines are routed parallel to each other. The line on the left is exposed, the one on the right is buried and marked with the surface sign. In general, open spans are estimated to increase the potential shaking damage state by up to 1 level, compared to a buried pipeline damage state condition.

When the pipelines cross under railroads, roadbeds, and sometimes power line rights-of-way, many of the right-of-way owners required the pipeline to be cased inside a larger pipe in the belief that this adds safety and/or it reduces the lifeline interactions if damage on one lifeline should occur (there is a current technical question whether the casing increases or reduces the overall safety of the crossing). Figure 23 shows a location where a 36-inch natural gas transmission line crosses under two different rail beds. One railroad requires the use of the extra casing, the other does not. If the use of a casing increases the safety of the crossing, the close proximity of the railroads means that the extra benefit is lost. If the use of a casing decreases the safety of the crossing, then the railroad expecting extra safety has not achieved it because of the close proximity in this situation.

Two of the most critical collocations involving fuel pipelines were shown in Figures 17 and 18. In Figure 17 the pipeline and the railroads are located directly below a landslide prone area that includes electrical transmission towers. Figure 18 shows that both types of fuel pipelines and high voltage electrical transmission systems all cross the San Andreas fault rift zone at approximately the same location. The results of these conditions are discussed below.

The western most 36-inch natural gas pipeline from valve station 14 (near the Cajon railroad summit east of the I-15/Highway 138 interchange) south to the end of the study area was installed in 1960. The eastern most 36-inch natural gas pipeline was installed in 1966. They operate at a mean operating pressure of 845 psig. The 16-inch distribution supply line branches off of those lines at Valve 15 (south and west of the I-15/I-215 interchange) and provides service to San Bernardino. It operates at a mean operating pressure of 350 psig. The line from the north of the study area (along Baldy Mesa Road) to valve station 14 was installed in 1976. It operates at a mean operating pressure of 936 psig. All of the lines were arc welded and constructed from high grade steel pipe. They deliver 0.6-1.0 billion cubic feet of natural gas per day.

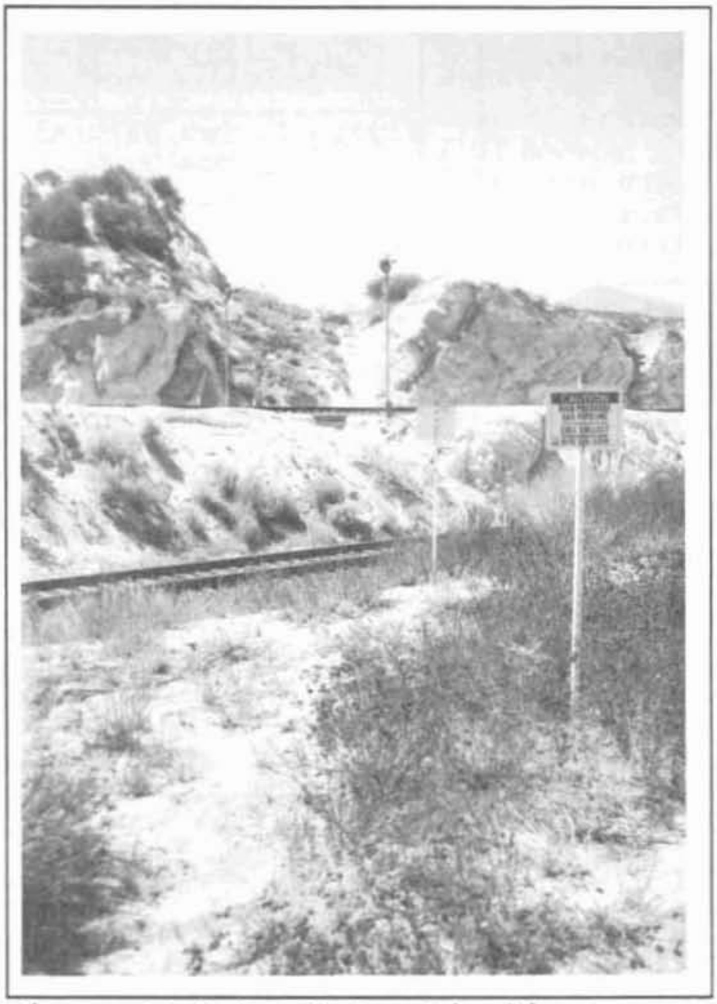

Figure 23 Natural Gas Pipeline Crossing Under Railroad Beds

The 8-inch petroleum products pipeline was installed in 1960 and the 14-inch line was installed in 1969. In 1980, several miles of the 8-inch line were abandoned and a new line was routed from the west side of Cajon Creek to join the 14-inch line on the east side. On the east side of Cajon Creek they are routed along the Cajon Blvd. extension. The lines transport a number of refined products, the transport a number of refined products, the principal ones being gasoline and jet fuel. They are made of high grade carbon steel. They operate at 1060-1690 psig. The lines pump about 80,000 barrels of fuel per day.

Most of the pipeline highway or railroad bed crossings are cased crossings. However, none of the Southern Pacific crossings are cased, and a few of the I-15 and Highway 138 crossings are uncased. That occurred because the Southern Pacific did not require casing when they authorized the right-of-way crossing, and when I-15 replaced Highway 66 and when Highway 138 was recently realigned (in 1990-1991) they did not follow all of the old routes. At new crossings the pipeline was already installed, and new casings were not required to be retrofit.

In the regions of MMI = VII or less, the shaking damage state for a buried gas or petroleum products transmission line is 1, and no collocation damage is estimated except for unusual conditions to be described below.

Following the pipelines from the center of the northern part of the study area and heading south, the first location for significant damage occurs at the crossing of the San Andreas fault. Here the 12 meter fault displacement is assumed to rupture the lines. The location includes the 36-inch natural gas pipeline and the two petroleum products pipelines (all of which rupture) and the Victorville-Century 287.5 kV lines 1 and 2. The damage scenario includes assuming that an explosion/fire occurs in addition to the discharge of petroleum products. The need to mitigate the impact of the fire and adverse environmental conditions and the delays caused by the general congestion in the area results in an assumed 37 day delay before restoration work can begin. Because of the high probability (100%) of the damage state, the incremental increase in the lifeline restoration time is also 37 days.

At Blue Cut the natural gas pipeline is next to the railroad bed and at the toe of a landslide area. High voltage power lines are located above the gas line in the slide area. A damage state 4 is predicted for the pipeline. The heavy equipment used to clear the railroad bed is assumed to increase the damage state to level 5. This increases the pipeline repair time by 18 days, and the debris clean up adds another 20 day delay. The general congestion adds a 7 day delay. This results in a change in the most probable restoration time of 12 days. Further south the pipeline follows the railroad bed along the west edge of Cajon Creek. About 4 miles further south, the pipeline and railroad are again at the toe of a landslide region. In this case only the 18 day increase in repair time and the 20 day debris removal delay are assumed. This results in an 8 day increase in the probable restoration time for that pipeline, for a total increase in time of 20 days.

Moving from the north to the south, the eastern most natural gas pipeline first experiences a potential collocation damage condition where it crosses I-15 in the region where the fiber optic conduits cross under I-15 in a concrete culvert and the electric power lines cross over the highway. This is a region of potential liquefaction. The damage state is 7 but the probability of damage is only 20% for the pipeline (but 40% for the lifelines that are right in the local creek bed). The pipeline is somewhat removed from the other lifelines, but there are railroad bridges also in the general area. It is assumed that the other lifeline repairs will be based on the requirement that long lengths of the natural gas pipeline will need to be exposed and examined to assure that a leak/explosion potential does not exist while they work on the other lifelines. This leads to a 20 day delay in starting the pipeline repair, resulting in a probable restoration delay of 8 days. About 3.2 miles further south the pipeline passes through another landslide zone near where it crosses I-15, leading to a probable increase in the restoration time of 16 days.

Across Cajon Creek from where the western pipeline was exposed to a potential landslide, the eastern natural gas pipeline crosses perpendicular to the two petroleum product pipelines and the fiber optic cables. This is a potential liquefaction zone that results in a pipeline damage state of 7 with a probability of 20%. There is a 30 day delay while the petroleum product spill is cleaned up and another 7 day delay for general congestion resolution questions. This results in an incremental change in the probable restoration time of 1 day.

Just south of the I-15/I-215 interchange the 16-inch natural gas pipeline crosses a local liquefaction zone. It is collocated with the two petroleum products pipelines, the railroads, and two of the fiber optic cables. The liquefaction results in a damage state 7 with a probability of 40%. The collocation damage scenario assumes a 30 day delay to clean up the petroleum product spills, and another 20 days to account for the congestion and delays experienced because of the repair to the nearby bridges. The net increase in restoration time is 8 days.

The two petroleum products pipelines enter the study area from the south in the Cajon Creek Wash. The 14-inch lines is collocated along the railroad right-of-way, the 8-inch is on the western side of the wash. Just south of the I-15/I-215 interchange, the 14-inch pipeline enters a local liquefaction zone, along with the 16-inch natural gas pipeline, the railroads, and two fiber optic cables. Damage state 7 (40% probability) occurs in this region. There is a 20 day delay due to the general level of congestion, and because the 14-inch pipeline is collocated with the railroad, there will be a requirement to expose and inspect the pipeline before it can be put back into service. This will add another 40 days of delay. This results in a 10 day increase in the probable time to restore service. About 6 miles further north, both pipelines enter another liquefaction region, along with a 36-inch natural gas pipeline and the collocated four fiber optic conduits. The low probability of liquefaction (20%) and the delay due to congestion (7 days) results in a 1 day increase in the probable restoration time. The pipelines enter a third liquefaction zone near Blue Cut. There the petroleum products pipelines cause delays in the repair of the fiber optic cables. The fiber optic cables do not impact the pipelines, and there is no collocation impact on the pipelines.

At the San Andreas Fault the pipelines are collocated with high voltage power lines and a 36-inch natural gas pipeline. Because the petroleum pipelines are located for several miles along the fault rift zone, there will be a lengthy delay of several months while the suitability of allowing them to relay the pipeline along that route is resolved with the regulatory authorities. However, that is not a collocation issue unless the pipelines are to be rerouted near the existing natural gas pipeline. However the damage scenario includes an explosion/fire, which will increase the amount of pipeline that must be exposed and inspected. In addition, the general congestion and environmental mitigation activities will cause a 30 day delay, for a probable increase in the pipeline restoration time due to collocation of 30 days. Thus, the total increase in the probable time to restore service for these pipelines is about 41 days, most of that impact is due to conditions at the fault rift zone.

Ninety-three collocations involving fuel pipelines were analyzed during this study. A summary of the collocation impacts is:

Lifeline	Increase in Probable Time to Restore Service, days	Increase in Probable Time to Restore Service, %
Western Natural Gas 36-inch Pipeline	57	86
Eastern Natural Gas 36-inch Pipeline	25	83
Natural Gas 16-inch Pipeline	8	80
Petroleum Products Pipelines	41	63

Transportation Lifelines

The Cajon Pass has been used for critical transportation routes since early times. At present it is used by the Southern Pacific, Santa Fe, and Union Pacific railroads, and Interstate Highway I-15. In addition, there are connecting highways, including the I-215 spur into San Bernardino, State Route 138 coming from the west into the Pass from Palmdale and continuing to the lake district in the east, and a partially abandoned section of old Federal highway U.S. 66, now called the Cajon Blvd. extension. The routes of these lifelines in Cajon Pass is shown in Figure 24. The location of the photographs presented in this section of the report are also shown on the figure.

Because these routes are discontinuous in the sense that each bridge, each change in MMI intensity, and each local liquefaction or landslide area must be separately checked. The railroads had to be segmented into 30 separate analysis sections and the I-15 highway into 36 separate analysis sections. During the vulnerability analysis of these facilities, it was necessary to consider some extension outside the study area in order to provide realistic estimates of time to restore service. In the case of the Southern Pacific Railroad, for example, the route considered was extended to the Highland Boulevard over-crossing in San Bernardino. The assumptions with regard to equipment available to make repairs differs from that used for the pipeline and communication lifelines in that it is assumed that the railroads and highways both have local active maintenance yards with their own heavy equipment for construction activities. While some of this may be pressed into service for life saving activities in the early emergency phase, it is not likely that this will prevent immediate inspection and reconnaissance. Therefore, no delay time waiting for equipment availability was assumed.

Moving this equipment to the most critical sites along the transportation lifeline, on the other hand, may present a significant problem of access because the equipment must move along the lifeline facility itself. In each analysis, it is first assumed that the equipment must work from one end or the other of the Cajon Pass, repairing each section as it goes before it can reach the next section. The probable access time to a given section is the sum of the products of times to repair all sections up to that point multiplied by their respective probability of damage. For the conditions existing in the Cajon Pass, this leads to very long access times for those sections remote from the Pass entrances. A second analysis was therefore made in which the possibility of construction of temporary by-passes around damaged sections to permit the access of construction equipment to more critical sites was considered (this, of course, only applies to the highway portions of the transportation lifelines). The access time to a given site in that situation became the sum of the products of the by-pass times and the probability that each of them is required because of the damage in the section being analyzed. Some of the highway bridges on I-15 have built in by-pass capability, since they are part of "diamond" interchanges in which the ramps may serve this purpose. In the generally dry conditions of Cajon Pass, it is possible in many cases to simply drive across country in tracked vehicles and lightly loaded four wheel drive trucks. Some road bed material would need to be placed to support heavy highway construction equipment.

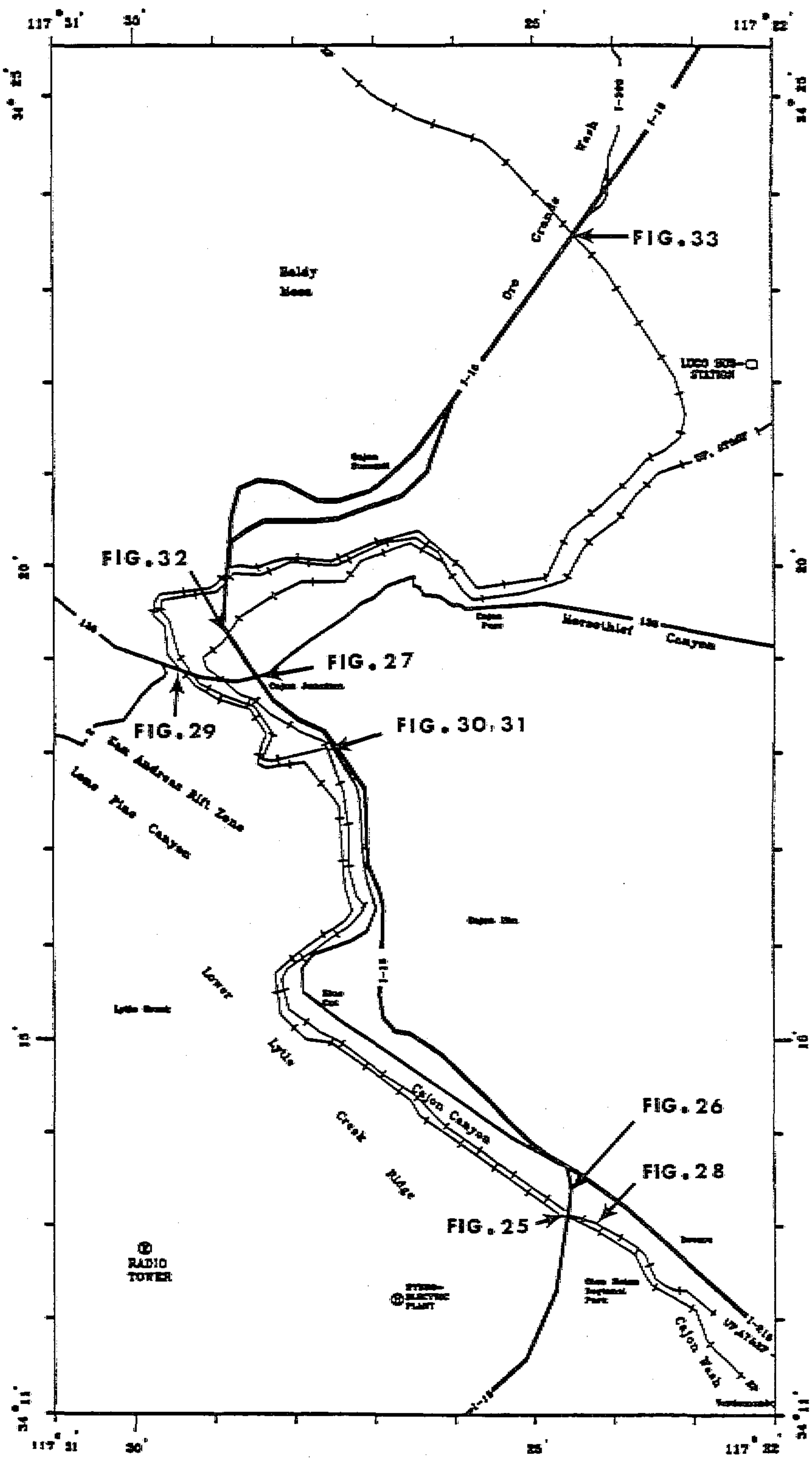

Figure 24, TRANSPORTATION LIFELINE ROUTES

SCALE

0 1 2 MILES

0 1 2 KILOMETERS

N

EXPLANATION

I-15 INTERSTATE

2 PAVED HIGHWAY

RAILROAD

Larger Scale Figure Located at End of Document

The purpose of these extended access time analyses was to find the critical total time for the lifeline section being evaluated, that is, the time to gain access to the site with repair equipment plus the time to carry out the needed repairs. As in the case of pipelines and power lines, each lifeline was first divided into sections, such that the conditions within each section were reasonably homogeneous. Because of the presence of many bridges on the highways and railroads, this leads to more sections for the roughly 25 miles of length of each separate transportation system. Prior to the detailed analysis of the lifeline section being

Figure 25 I-15 Bridge Over The Railroads In Cajon Wash

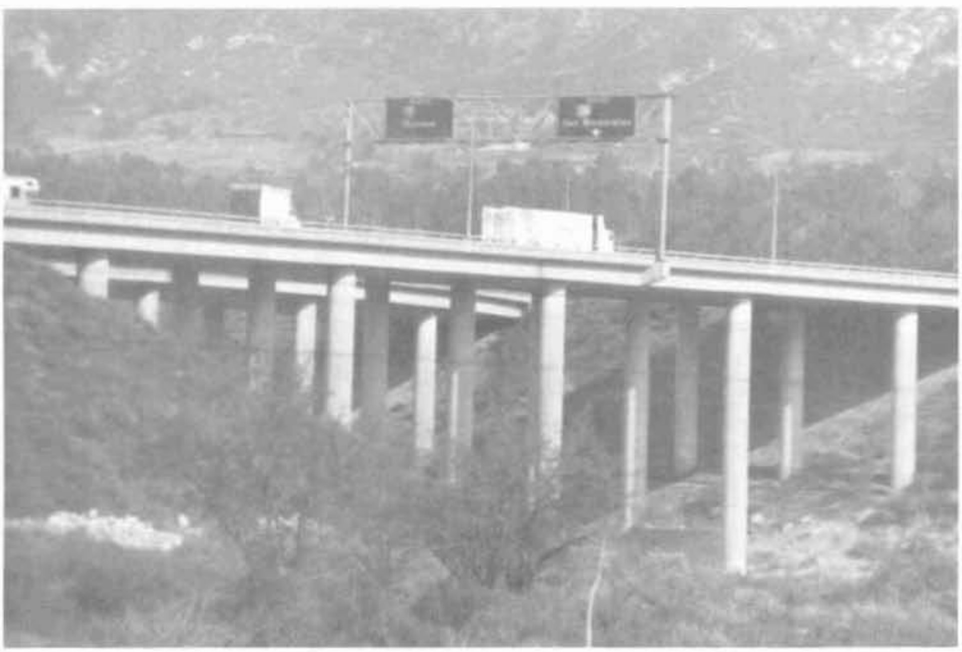

Figure 26 I-15 Bridge Over Cajon Wash

considered, the Bridge Vulnerability Index of each of these structures had to be determined, and the probable extent and type of damage to each postulated.

The highway bridges along Interstate I-15 were, for the most part, built in the late 1960's, except for the section over Lytle Creek Wash. Although they are in an area generally considered to be "California region 7", the status of retrofit is somewhat irregular. In this analysis, they are considered to be "California region 3-6" until proved to qualify for the higher degree of safety. Nevertheless, none of these bridges are expected to completely collapse, although partial collapse of several is possible. The I-15 bridge over the railway lines (Figure 25) and the high level I-15 bridge over Cajon Wash (Figure 26) are vulnerable, and there is some possibility of the partial collapse of the steel girders over I-15 at its junction with highway 138 (Figure 27).

Many of the railroad bridges in the Cajon Pass are over 50 years old, but most are in relatively good condition. As noted in the discussion of the development of the Bridge Vulnerability Index, many of these bridges have inherent resistance to lateral loads. There are, however, several multiple simple span bridges over poor soil conditions (including possible liquefaction), such as both the Southern Pacific and Santa Fe bridges over the lower end of Cajon Wash (Figure 28). There are several more such crossings over the Cajon Creek and its branches. There is also a large two span, through plate, girder bridge on the Southern Pacific railroad over Highway 138 which is sharply skewed, and which has bearings which are vulnerable to loss (Figure 29). It is expected that the multiple span structures will have one or more spans dislodged where they are subjected

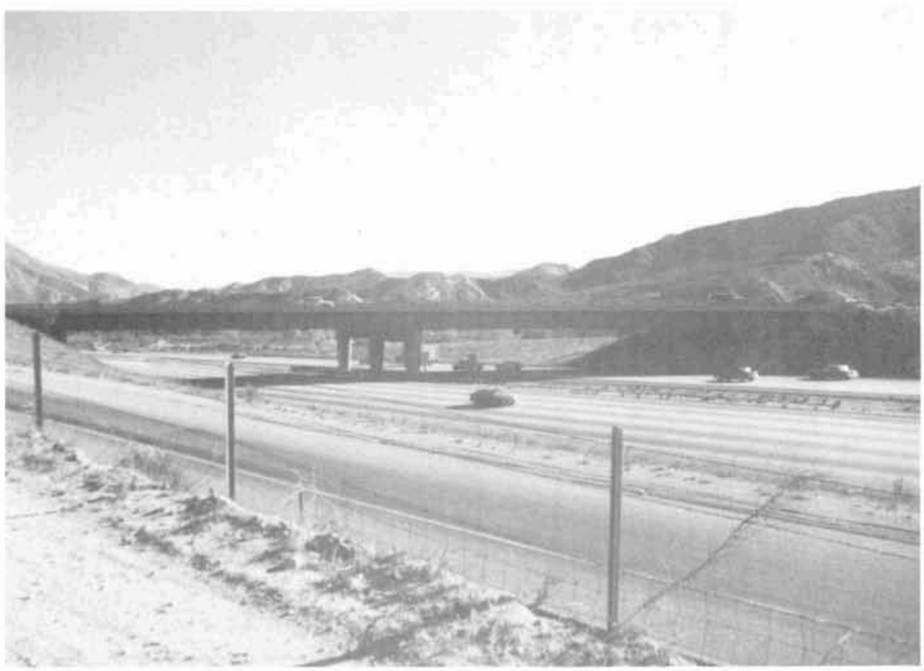

Figure 27 Highway 138 Bridge Over I-15

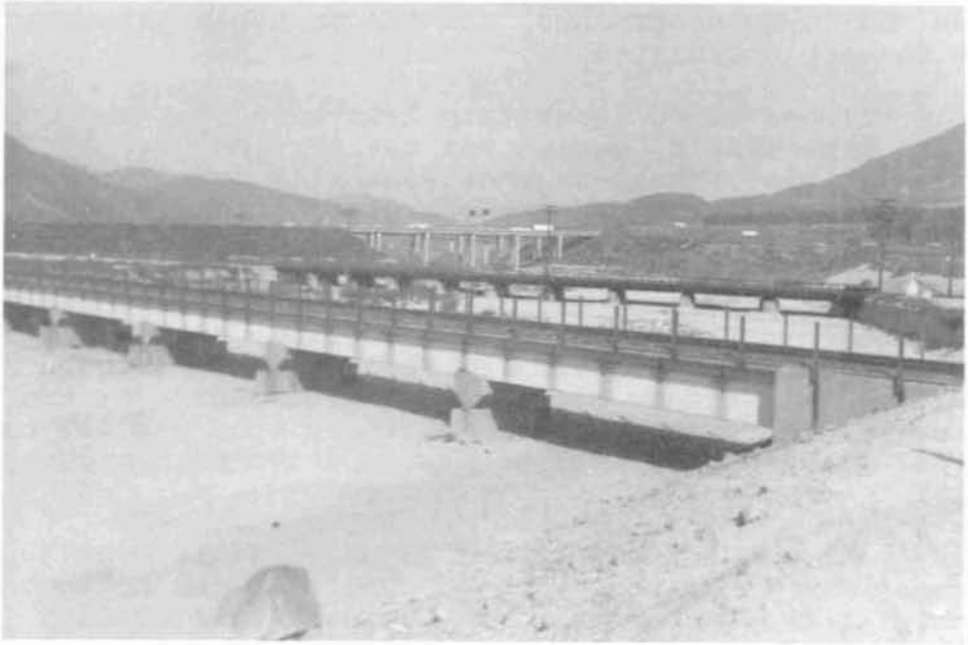

Figure 28 Railroad Bridges In Cajon Wash (I-15 Bridge In The Background)

Figure 29 Railroad Bridge Over Highway 138 (Collapse Expected)

to MMI= VIII shaking intensity zones or are on potentially liquefiable soils. The failure of the Bridge shown in Figure 29 was responsible for much of the access time estimate for repair of I-15, since it blocked Highway 138 from being an immediate detour route for equipment needed for the I-15 repairs.

Figure 30 Santa Fe Railroad Rubble Masonry Pier Bridge

There is one bridge on the Santa Fe railroad just south of the I-15 truck weighing station which is founded on rubble masonry piers on sandy soil with a high water table (Figure 30). Loss of one or more spans is anticipated. That is contrasted to the Union Pacific railroad bridge at the

Figure 31 Union Pacific Railroad Bridge With Power Lines Overhead

same location (Figure 31) which has steel column, pile piers. Figure 14 shows surface conditions near these two bridges.

The calculations for the vulnerability analysis and time to restore service involve only simple arithmetic, but they are quite time consuming if carried out manually. For this report, the analyses were done on a computer spreadsheet, which greatly aided an orderly and efficient approach.

The primary objective of the study was to determine how the times to restore full service would be affected by the collocation of several types of lifelines in the same congested corridor. The interaction scenarios have been discussed in this report in earlier sections. There are, however additional problems because of the highway-railroad interactions. For the Cajon Pass application, these interactions occur at the same general areas as the previously identified critical clusters:

(1) The area near the liquefiable zone just south of the highway I-15 crossing over the railroads and the Cajon Wash, near the junction with I-215. This includes intersection points 8, 9, 10, 11, 13, 14, 15, 16, 18, and 19. A partial collapse of highway bridge No. 54-0818 over the three rail lines adds to the problems at this location. A delay time of 30 days due to this bridge problem (Figure 25) was added to the previously noted 30 day delay due to pipeline damage and hazards.

(2) The section of the steep slide prone slopes along the west side of Cajon Canyon (see Figure 17) and the liquefiable zone on the east side about one mile north of the junction of I-15 an I-215. This includes intersections 22, 25, 26, 27, 28, 29, 30 on the east side and 31, 32, 33, 34, and 35 on the west side of the canyon. The 30 day delay previously established appears adequate.

(3) The conditions in Blue Cut are so congested, combined with the expected explosion and/or fire, that an increase in the expected damage states for the railroads by one level is justified. Intersections 38, 39, 93, and 99 are involved. A 60 day delay in access is also assumed.

(4) At the San Andreas fault zone, intersections 37, 40, 41, and 91 are involved. Problems with fuel pipelines and power lines have already been noted. The 30 day delay in initiating repairs to other lifelines was applied to the railroads.

(5) The area just north of the section of Highway 138 and west of Highway I-15. Problems with pipelines and power lines have already been noted at intersection points 47, 48, 49, 51, 52, and 53. There is also a possibility of partial collapse of the Southern Pacific railroad bridge over Highway 138 (Figure

29). An additional delay time of 30 days was added for access involving this bridge, over and above the 30 days to clear fire hazards related to pipeline damage.

(6) There are several other minor critical areas:

(a) The area just west and south of the I-15 truck weighing station. The crib retaining wall could slump (see Figure 14). The principle effect is on Southern Pacific railroad sections 15 (westbound) and 24 (eastbound). A 30 day delay was assumed.

(b) Highway Structures 0796, 0797 and 0827 which carry I-15 over the rail lines at Alray and Gish at intersections 55 and 57 (Figure 32). These structures may only be lightly damaged, but a 10 day delay in railroad access is assumed to permit time for inspection and temporary shoring if required.

(c) The I-15 bridge 0664 (Figure 33) over the Southern Pacific tracks north of the pass at intersection 83 is expected to be lightly damaged, but 10 days delay is allowed for inspection (also see Figure 15 which shows details of this bridge).

The effect of these collocation delays on the restoration of the transportation lifelines was evaluated by making a analysis with collocation assumed. This is a "second pass" analysis with the spreadsheet. A special problem developed in reassessment of the alternate route by way of highway 138, in that access to the connection point on the Santa Fe was blocked by the expected partial bridge collapse on the Southern Pacific. For this reason the delay time associated with this problem was added to the previous estimated time to reach the connection point, that is 10 days plus 60 days delay time. This gives 70 days. The cumulative access times for this route were then computed as before, working both ways from this point.

A summary of the results of the study are presented below.

Lifeline	Increase in Probable Time to Restore Service, days	Increase in Probable Time to Restore Service, %
Highway I-15	35	22
Southern Pacific Railroad	17	8
Atcheson Topeka & Santa Fe Railroad	85	33

The smaller percent increase in time to restore service for the Southern Pacific railroad compared to the other transportation lifelines. is due in part to its more favorable location with respect to other lifelines; but it should also be noted that the probable partial collapse of one the bridges on this line contributes to large access time required for the others.

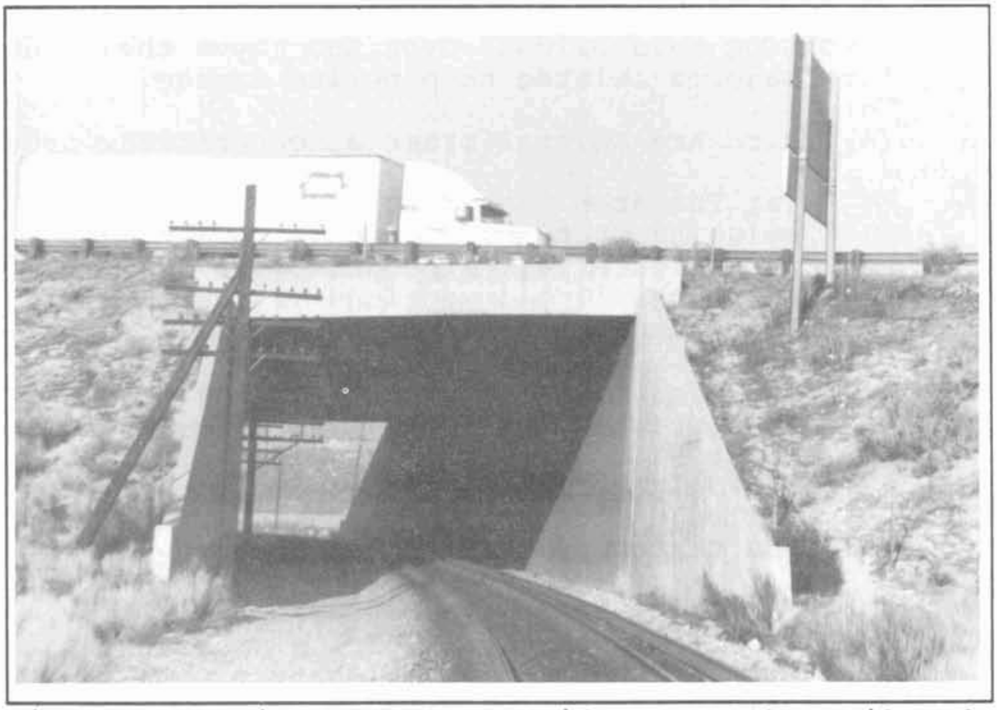

Figure 32 Typical I-15 Box Bridge Over the Railroads

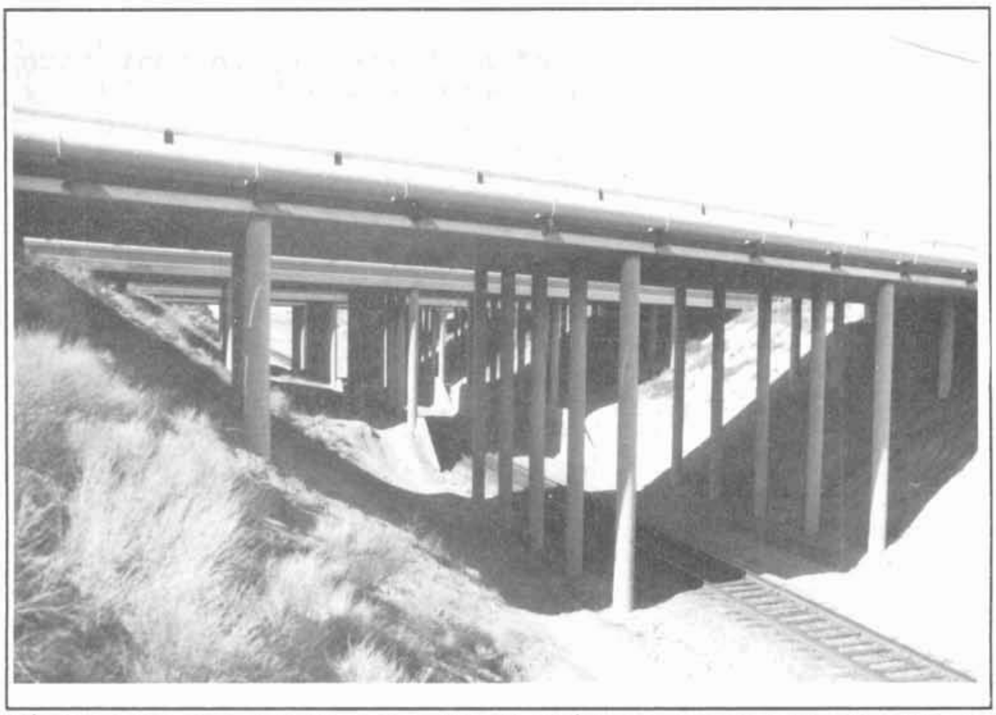

Figure 33 I-15 & Access Road Bridges Over the Southern Pacific Railroad

5.3 Chapter 5.0 Bibliography

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6.0 FUTURE STUDY NEEDS

Recognizing that this is the first comprehensive analysis of the impact of lifeline collocation on the individual lifeline's vulnerability, it is recommended that the follow-on studies be performed.

1. The collocation analysis should be repeated at another location outside of California. It will provide information on the following items:

    Is there enough data available to conduct the analysis, or was the data base available in California unique?

    Can the methods suggested by Rojahn to adjust the California data to other regions be applied to develop reasonable results?

The site can include water and sewer systems or reservoirs to assure that the collocation analysis method can properly treat the impacts of these lifelines, which were not available at the Cajon Pass.

The study can check the suitability of the LSI-MMI relationship developed for analyzing liquefaction-induced damage, the Bridge Vulnerability Index method, and the lifeline zones of influence, all of which were developed with the Cajon Pass situation in mind.

If possible, the study site should include lifeline passage over a large water body, or at least over wet ground. This will help clarify the impacts of equipment and material access time compared to lifeline repair time, as the dry ground of the Cajon Pass did not impose very restrictive "detour" conditions.

2. In parallel with the above study to further refine the collocation analysis method, a second study is warranted. It should focus on presenting the material to a broad audience. Special emphasis should be given to contacting lifeline owners and operators to discuss the study and the results obtained. Their perspective and response should provide valuable information on where improvements in the analysis method would clarify important issues that relate to the siting of lifelines in "lifeline corridors". It should also help identify mitigation approaches that reflect the operational and economic needs of the lifeline providers.

3. A longer term study is needed to provide more detailed data and expert opinion for lifelines. Most of the current data emphasizes earthquake impacts on buildings and secondly on bridges. Most of the present data (including most of the lifeline data) in the data bases were obtained from the building and bridge technical sectors. An new study to examine the present data base presented in ATC-13, but with full emphasis on lifelines, should be undertaken to allow the lifeline portions of earthquake analysis to have the same level of technical input that buildings and structures presently have.

Appendix A

Modified Mercalli Intensity (MMI) Index Scale

Modified Mercalli (MM) Intensity Scale *

I. Not felt—or, except rarely under especially favorable circumstances. Under certain conditions, at and outside the boundary of the area in which a great shock is felt:
   sometimes birds, animals, reported uneasy or disturbed;
   sometimes dizziness or nausea experienced;
   sometimes trees, structures, liquids, bodies of water, may sway—doors may swing, very slowly.

II. Felt indoors by few, especially on upper floors, or by sensitive or nervous persons.
   Also, as in grade I, but often more noticeably:
   sometimes hanging objects may swing, especially when delicately suspended;
   sometimes trees, structures, liquids, bodies of water, may sway, doors may swing, very slowly;
   sometimes birds, animals, reported uneasy or disturbed;
   sometimes dizziness or nausea experienced.

III. Felt indoors by several, motion usually rapid vibration.
   Sometimes not recognized to be an earthquake at first.
   Duration estimated in some cases.
   Vibration like that due to passing of light, or lightly loaded trucks, or heavy trucks some distance away.
   Hanging objects may swing slightly.
   Movements may be appreciable on upper levels of tall structures.
   Rocked standing motor cars slightly.

IV. Felt indoors by many, outdoors by few.
   Awakened few, expecially light sleepers.
   Frightened no one, unless apprehensive from previous experience.
   Vibration like that due to passing of heavy, or heavily loaded trucks.
   Sensation like heavy body striking building, or falling of heavy objects inside.
   Rattling of dishes, windows, doors; glassware and crockery clink and clash.
   Creaking of walls, frame, especially in the upper range of this grade.
   Hanging objects swung, in numerous instances.
   Disturbed liquids in open vessels slightly.
   Rocked standing motor cars noticeably.

V. Felt indoors by practically all, outdoors by many or most: outdoors direction estimated.
   Awakened many, or most.
   Frightened few—slight excitement, a few ran outdoors.
   Buildings trembled throughout.
   Broke dishes, glassware, to some extent.
   Cracked windows—in some cases, but not generally.
   Overturned vases, small or unstable objects, in many instances, with occasional fall.
   Hanging objects, doors, swing generally or considerably.
   Knocked pictures against walls, or swung them out of place.
   Opened, or closed, doors, shutters, abruptly.
   Pendulum clocks stopped, started, or ran fast, or slow.
   Moved small objects, furnishings, the latter to slight extent.
   Spilled liquids in small amounts from well-filled open containers.
   Trees, bushes, shaken slightly.

---

*Adapted from Sieberg's (1923) Mercalli-Cancani scale, modified and condensed. Quoted from Wood and Neumann (1931).

VI. Felt by all, indoors and outdoors.

Frightened many, excitement general, some alarm, many ran outdoors.
Awakened all.
Persons made to move unsteadily.
Trees, bushes, shaken slightly to moderately.
Liquid set in strong motion.
Small bells rang—church, chapel, school, etc.
Damage slight in poorly built buildings.
Fall of plaster in small amount.
Cracked plaster somewhat, especially fine cracks chimneys in some instances.
Broke dishes, glassware, in considerable quantity, also some windows.
Fall of knick-knacks, books, pictures.
Overturned furniture in many instances.
Moved furnishings of moderately heavy kind.

VII. Frightened all—general alarm, all ran outdoors.

Some, or many, found it difficult to stand.
Noticed by persons driving motor cars.
Trees and bushes shaken moderately to strongly.
Waves on ponds, lakes, and running water.
Water turbid from mud stirred up.
Incaving to some extent of sand or gravel stream banks.
Rang large church bells, etc.
Suspended objects made to quiver.
Damage negligible in buildings of good design and construction, slight to moderate in well-built ordinary buildings, considerable in poorly built or badly designed buildings, adobe houses, old walls (especially where laid up without mortar), spires, etc.
Cracked chimneys to considerable extent, walls to some extent.
Fall of plaster in considerable to large amount, also some stucco.
Broke numerous windows, furniture to some extent.
Shook down loosened brickwork and tiles.
Broke weak chimneys at the roofline (sometimes damaging roofs).
Fall of cornices from towers and high buildings.
Dislodged bricks and stones.
Overturned heavy furniture, with damage from breaking.
Damage considerable to concrete irrigation ditches.

VIII. Fright general—alarm approaches panic.

Disturbed persons driving motor cars.
Trees shaken strongly—branches, trunks, broken off, especially palm trees.
Ejected sand and mud in small amounts.
Changes: temporary, permanent; in flow of springs and wells; dry wells renewed flow; in temperature of spring and well waters.
Damage slight in structures (brick) built especially to withstand earthquakes.
Considerable in ordinary substantial buildings, partial collapse: racked, tumbled down, wooden houses in some cases; threw out panel walls in frame structures, broke off decayed piling.
Fall of walls.
Cracked, broke, solid stone walls seriously.
Wet ground to some extent, also ground on steep slopes.
Twisting, fall, of chimneys, columns, monuments, also factory stacks, towers.
Moved conspicuously, overturned, very heavy furniture.

IX. Panic general.

Cracked ground conspicuously.

Damage considerable in (masonry) structures built especially to withstand earthquakes:

threw out of plumb some wood-frame houses built especially to withstand earthquakes;

great in substantial (masonry) buildings, some collapse in large part; or wholly shifted frame buildings off foundations, racked frames;

serious to reservoirs; underground pipes sometimes broken.

X. Cracked ground, especially when loose and wet, up to widths of several inches; fissures up to a yard in width ran parallel to canal and stream banks.

Landslides considerable from river banks and steep coasts.

Shifted sand and mud horizontally on beaches and flat land.

Changed level of water in wells.

Threw water on banks of canals, lakes, rivers, etc.

Damage serious to dams, dikes, embankments.

Damage severe to well-built wooden structures and bridges, some destroyed.

Developed dangerous cracks in excellent brick walls.

Destroyed most masonry and frame structures, also their foundations.

Bent railroad rails slightly.

Tore apart, or crushed endwise, pipe lines buried in earth.

Open cracks and broad wavy folds in cement pavements and asphalt road surfaces.

XI. Disturbances in ground many and widespread, varying with ground material.

Broad fissures, earth slumps, and land slips in soft, wet ground.

Ejected water in large amount charged with sand and mud.

Caused sea-waves (tidal waves) of significant magnitude.

Damage severe to wood-frame structures, especially near shock centers.

Great to dams, dikes, embankments, often for long distances.

Few, if any (masonry), structures remained standing.

Destroyed large well-built bridges by the wrecking of supporting piers, or pillars.

Affected yielding wooden bridges less.

Bent railroad rails greatly, and thrust them endwise.

Put pipe lines buried in earth completely out of service.

XII. Damage total—practically all works of construction damaged greatly or destroyed.

Disturbances in ground great and varied, numerous shearing cracks.

Landslides, falls of rock of significant character, slumping of river banks, etc., numerous and extensive.

Wrenched loose, tore off, large rock masses.

Fault slips in firm rock, with notable horizontal and vertical offset displacements.

Water channels, surface and underground, disturbed and modified greatly.

Dammed lakes, produced waterfalls, deflected rivers, etc.

Waves seen on ground surfaces (actually seen, probably, in some cases).

Distorted lines of sight and level.

Threw objects upward into the air.

MODIFIED MERCALLI INTENSITY SCALE OF 1931

(Abridged)

I. Not felt except by a very few under especially favorable circumstances.

II. Felt only by a few persons at rest, especially on upper floors of buildings. Delicately suspended objects may swing.

III. Felt quite noticeably indoors, especially on upper floors of buildings, but many people do not recognize it as an earthquake. Standing motor cars may rock slightly. Vibration like passing of truck. Duration estimated.

IV. During the day felt indoors by many, outdoors by few. At night some awakened. Dishes, windows, doors disturbed; walls made cracking sound. Sensation like heavy truck striking building. Standing motor cars rocked noticeably.

V. Felt by nearly everyone; many awakened. Some dishes, windows, etc., broken; a few instances of cracked plaster; unstable objects overturned. Disturbance of trees, poles and other tall objects sometimes noticed. Pendulum clocks may stop.

VI. Felt by all; many frightened and run outdoors. Some heavy furniture moved; a few instances of fallen plaster or damaged chimneys. Damage slight.

VII. Everybody runs outdoors. Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable in poorly built or badly designed structures; some chimneys broken. Noticed by persons driving motor cars.

VIII. Damage slight in specially designed structures; considerable in ordinary substantial buildings with partial collapse; great in poorly built structures. Panel walls thrown out of frame structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned. Sand and mud ejected in small amounts. Changes in well water. Disturbed persons driving motor cars.

IX. Damage considerable in specially designed structures; well designed frame structures thrown out of plumb; great in substantial buildings, with partial collapse. Buildings shifted off foundations. Ground cracked conspicuously. Underground pipes broken.

X. Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations; ground badly cracked. Rails bent. Landslides considerable from river banks and steep slopes. Shifted sand and mud. Water splashed (slopped) over banks.

XI. Few, if any (masonry), structures remain standing. Bridges destroyed. Broad fissures in ground. Underground pipe lines completely out of service. Earth slumps and land slips in soft ground. Rails bent greatly.

XII. Damage total. Waves seen on ground surfaces. Lines of sight and level distorted. Objects thrown upward into the air.

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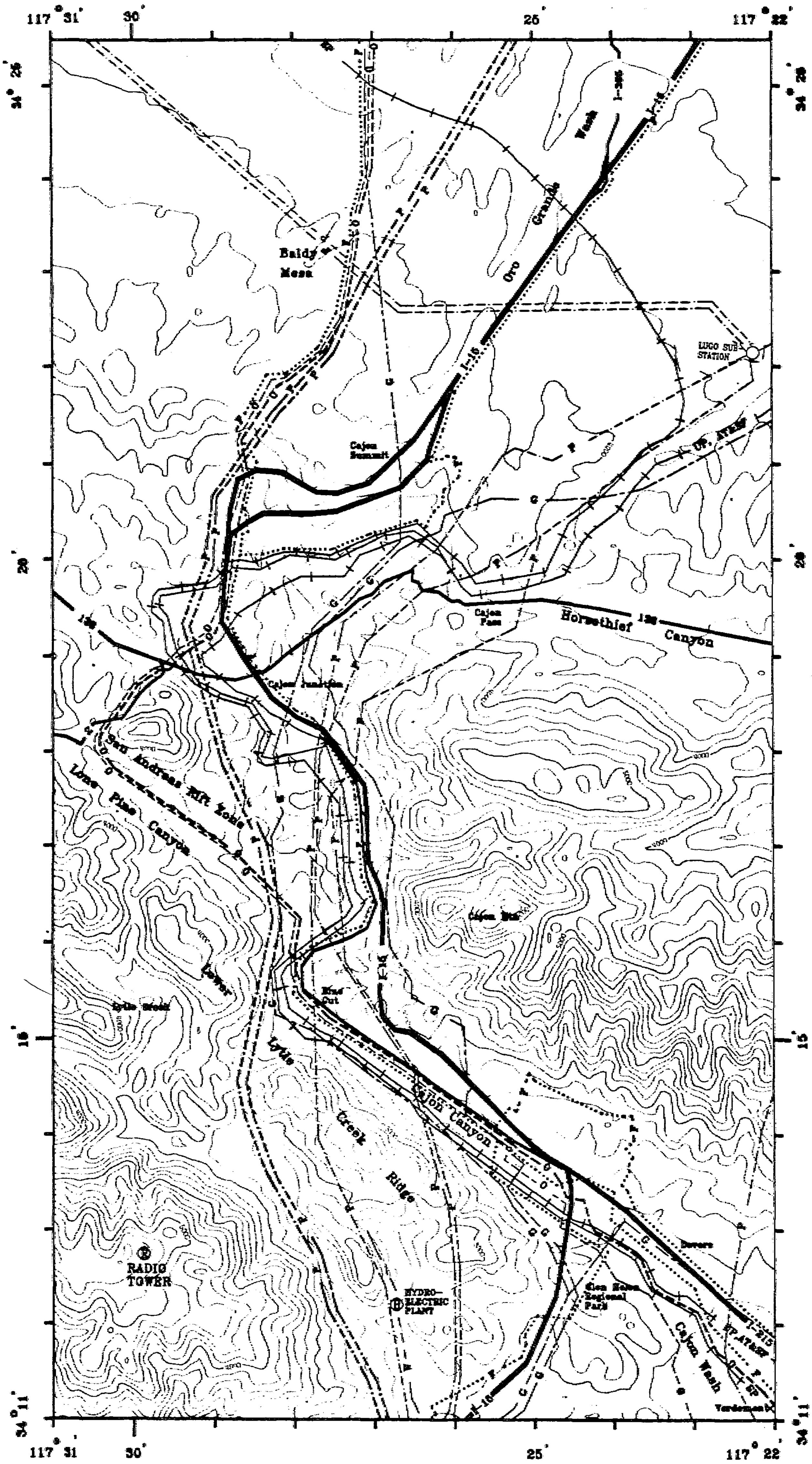


FIGURE 6, A COMPOSITE OF THE LIFELINE ROUTES AT CAJON PASS

SCALE

0 1 2 MILES

0 1 2 KILOMETERS

N

CONTOUR ELEVATIONS IN FEET
CONTOUR INTERVAL 200 FEET

EXPLANATION

I-15	INTERSTATE
2	PAVED HIGHWAY
	RAILROAD
P P	POWER LINES
W W	FLUME-PENSTOCK
O O	PETROLEUM PRODUCT PIPELINES
G G	NATURAL GAS PIPELINES
F F	FIBER OPTIC CABLE

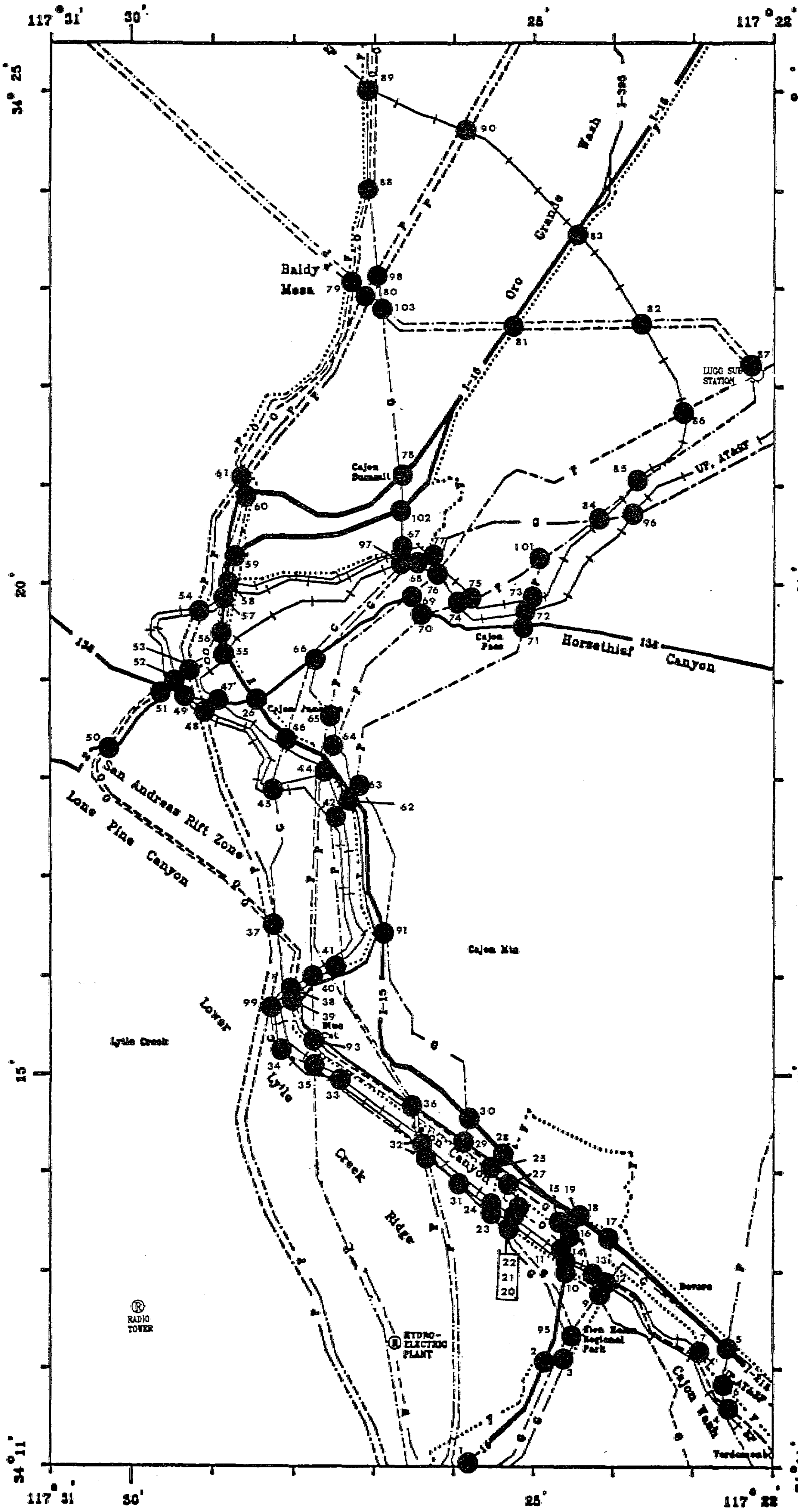


FIGURE 7, IDENTIFICATION OF LIFELINE COLLOCATIONS AT CAJON PASS

SCALE

0 1 2 MILES

0 1 2 KILOMETERS

N

EXPLANATION

I-15 — INTERSTATE

2 — PAVED HIGHWAY

COLLOCATION LOCATION

RAILROAD

P — POWER LINES

O — PETROLEUM PRODUCT PIPELINES

G — NATURAL GAS PIPELINES

F — FIBER OPTIC CABLE

W — FLUME-PENSTOCK

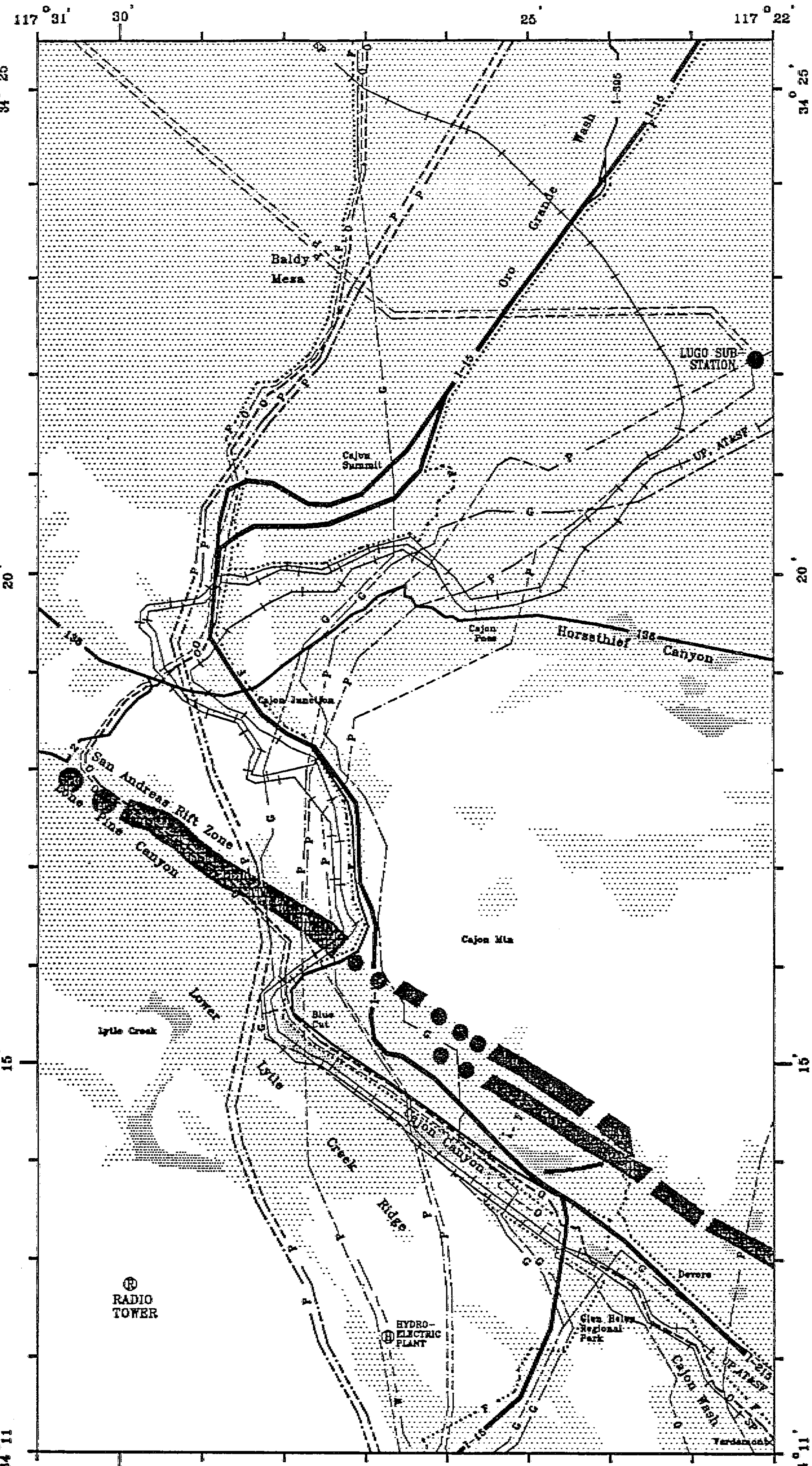


FIGURE 8, LIFELINE ROUTES WITH SHAKING INTENSITY AND POTENTIAL LANDSLIDE AND LIQUEFACTION AREAS

SCALE

0 1 2 MILES

0 1 2 KILOMETERS

N

EXPLANATION

I-15	INTERSTATE
2	PAVED HIGHWAY
	RAILROAD
P	POWER LINES
W	FLUME–PENSTOCK
O	PETROLEUM PRODUCT PIPELINES
G	NATURAL GAS PIPELINES
F	FIBER OPTIC CABLE

MODIFIED MERCALI SHAKING INTENSITY

IX VIII VII VI

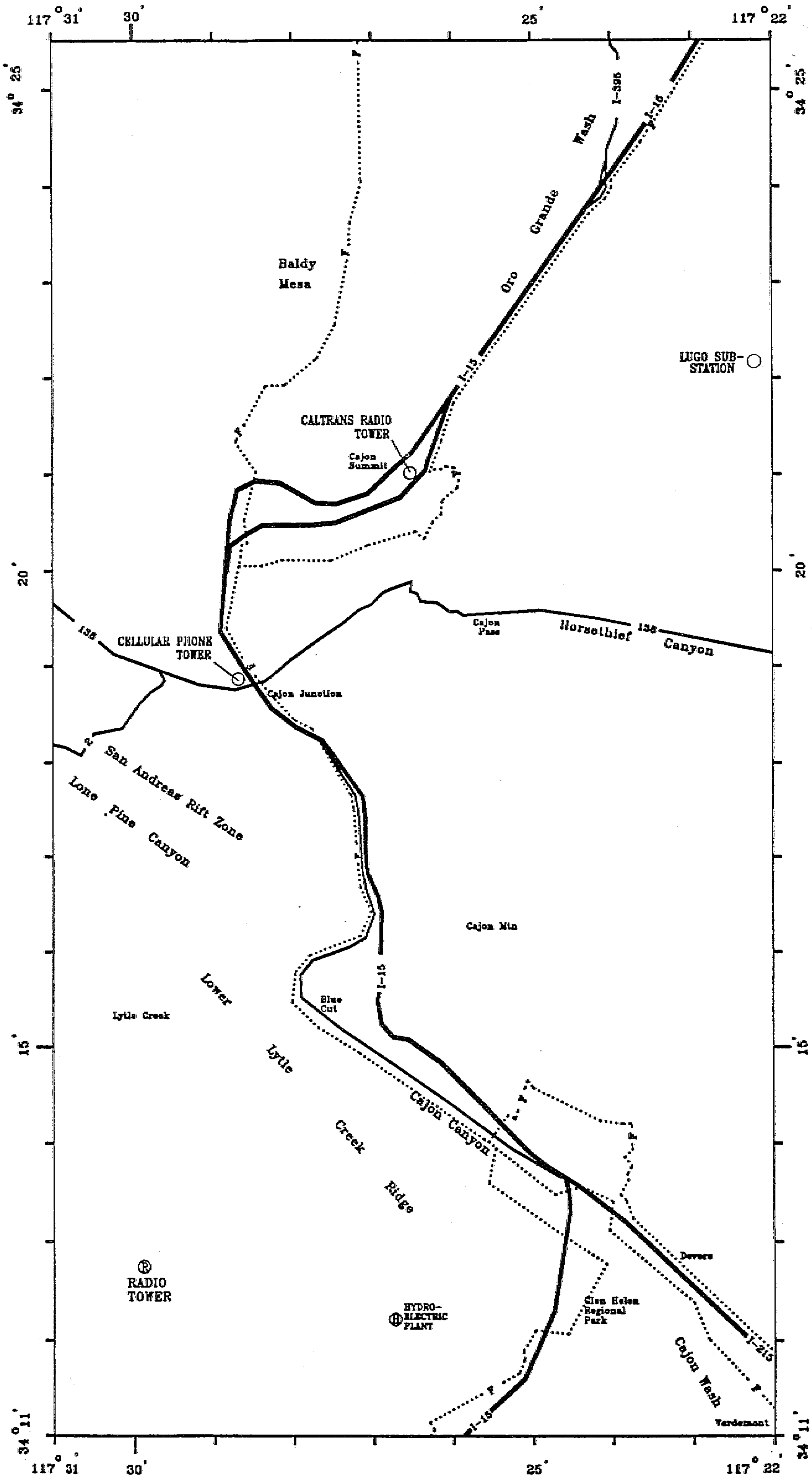


FIGURE 9, COMMUNICATION LIFELINE ROUTES

SCALE

0 1 2 MILES

0 1 2 KILOMETERS

N

EXPLANATION

I-15 INTERSTATE

2 PAVED HIGHWAY

F F FIBER OPTIC CABLE

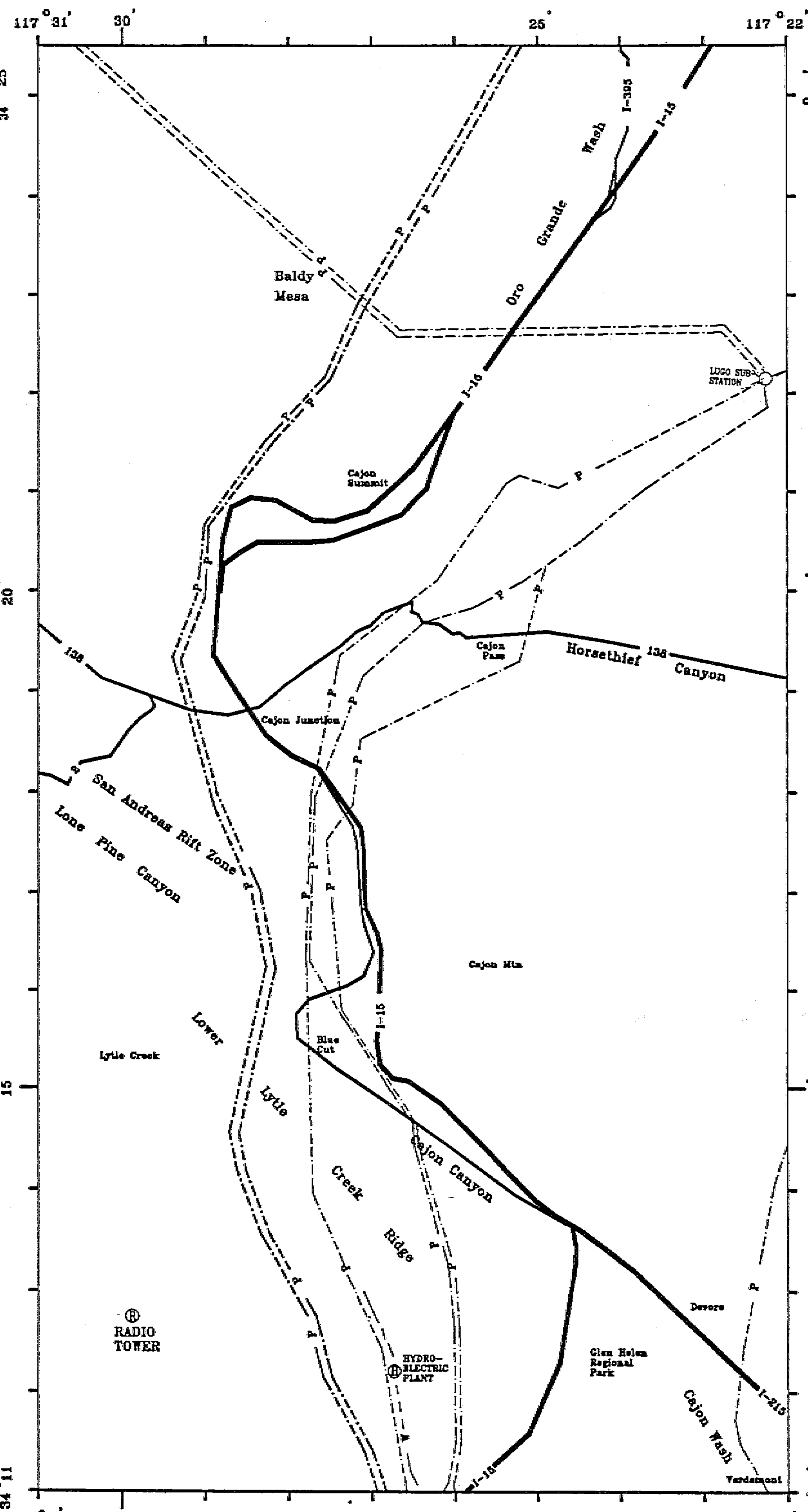
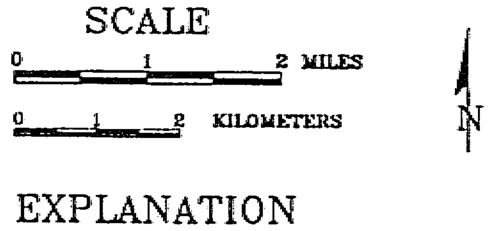


FIGURE 16, ELECTRIC POWER LIFELINE ROUTES



EXPLANATION

I-15	INTERSTATE
2	PAVED HIGHWAY
P — P	POWER LINES
W — W	BURIED AQUEDUCT

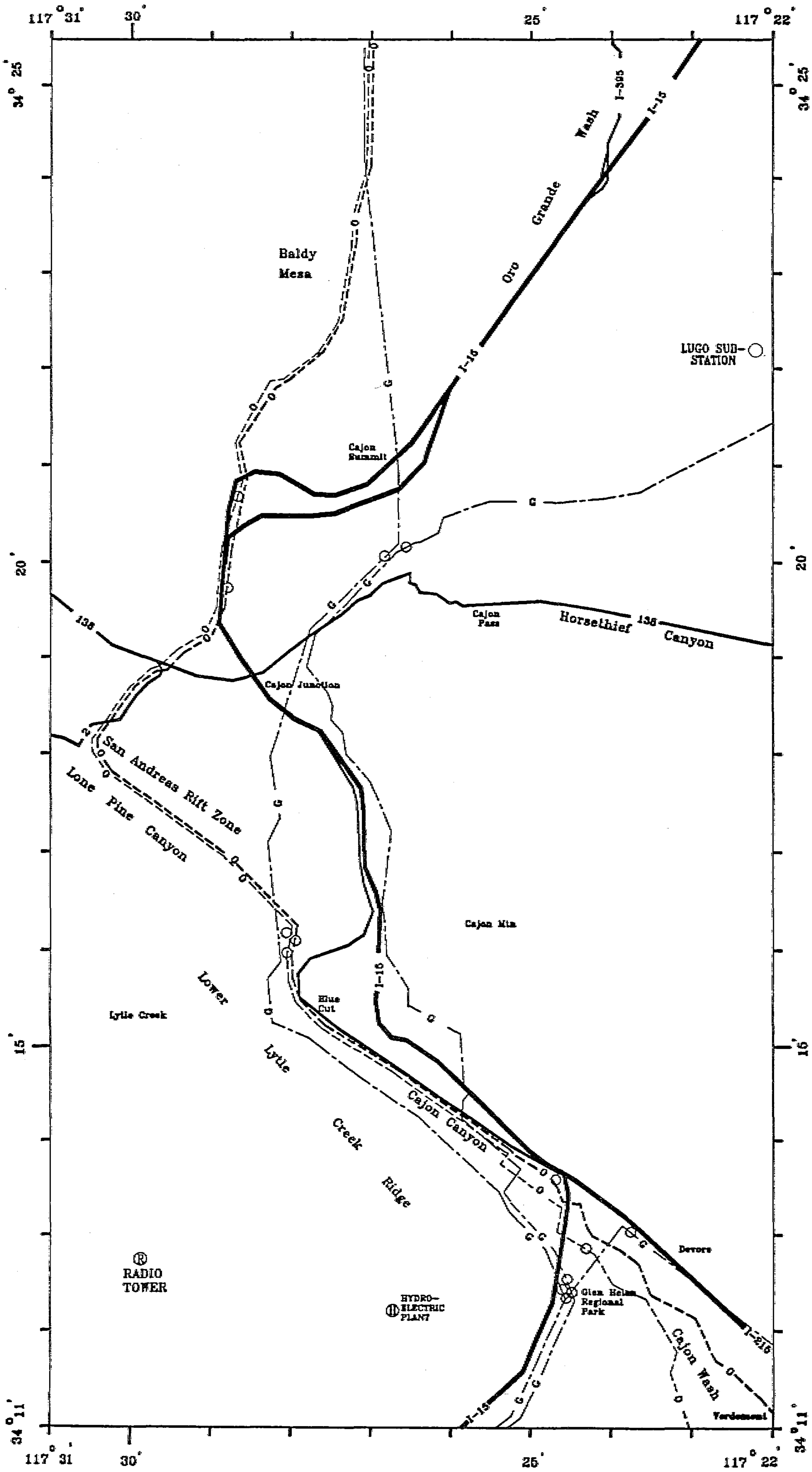


FIGURE 20, FUEL PIPELINE LIFELINE ROUTES

SCALE

0 1 2 MILES

0 1 2 KILOMETERS

N

EXPLANATION

I-15		INTERSTATE
2		PAVED HIGHWAY
O	O	PETROLEUM PRODUCT PIPELINES
G	G	NATURAL GAS PIPELINES
		VALVES

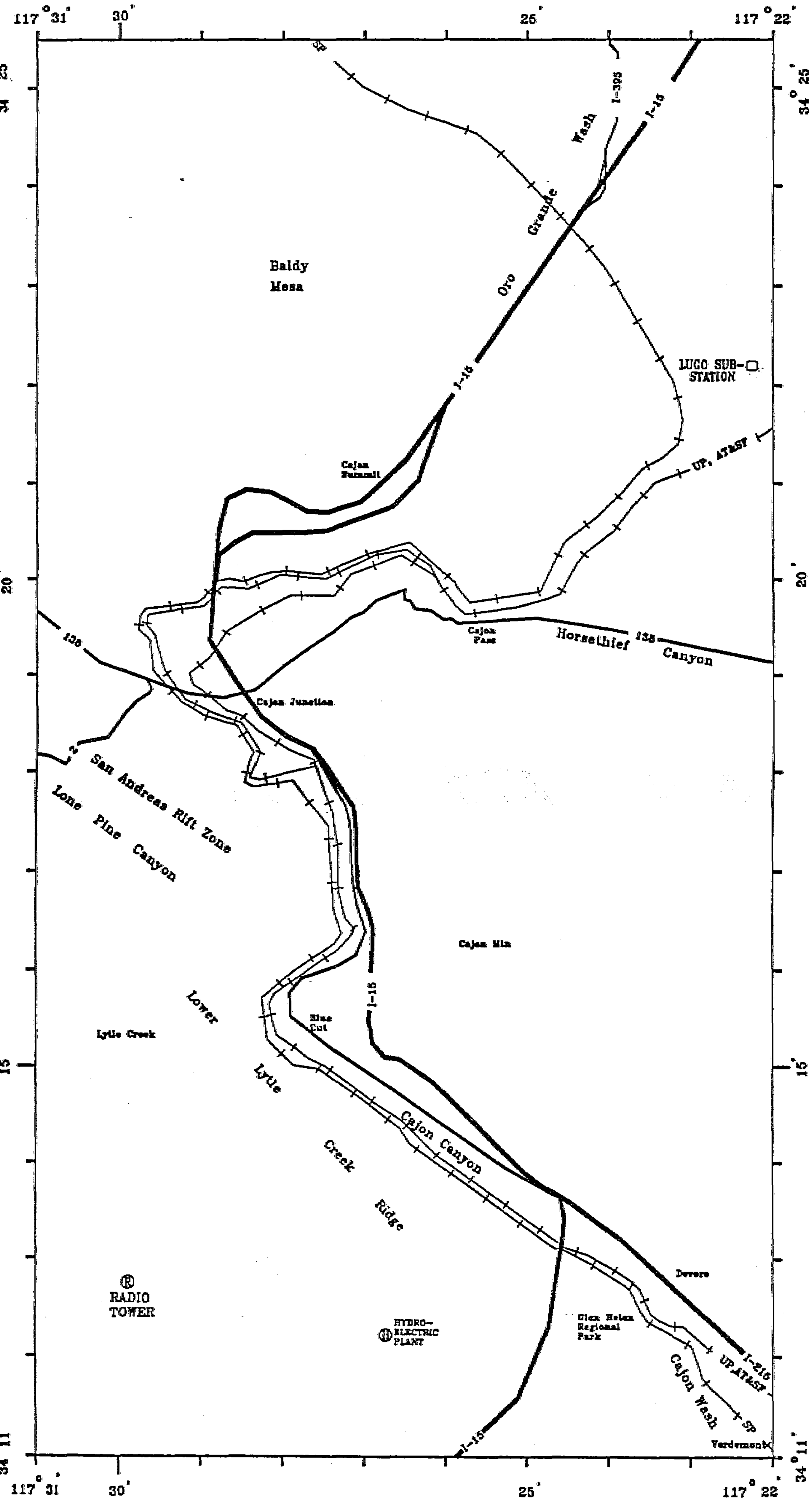


FIGURE 24, TRANSPORTATION LIFELINE ROUTES

SCALE

0 1 2 MILES

0 1 2 KILOMETERS

N

EXPLANATION

I-15	INTERSTATE
2	PAVED HIGHWAY
	RAILROAD